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SAGE System for assessing Aviation's Global Emissions

Version 1.5

Global Aviation Emissions Inventories for 2000 through 2004

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13. ABSTRACT (Maximum 200 words)

The United States (US) Federal Aviation Administration (FAA) Office of Environment and Energy (AEE) developed the System for assessing Aviation's Global Emissions (SAGE) with support from the Volpe National Transportation Systems Center (Volpe), the Massachusetts Institute of Technology (MIT) and the Logistics Management Institute (LMI). SAGE is a high fidelity computer model used to predict aircraft fuel burn and emissions for all commercial (civil) flights globally in a given year. The model can analyze scenarios from a single flight to airport, country, regional, and global levels. In addition, SAGE dynamically models aircraft performance, fuel burn and emissions, capacity and delay at airports, and forecasts of future scenarios. The purpose of SAGE is to provide FAA, and indirectly the international aviation community, with a tool to evaluate the effects of various policy, technology, and operational scenarios on aircraft fuel use and emissions. Currently at Version 1.5, SAGE is not for use on a stand alone personal computer; it is an FAA government research tool, not for release to the public. However, results from the model have been made available to the international aviation community; and, FAA is committed to the continued development, support and reporting of SAGE.

SAGE Version 1.5 has been used to generate global inventories of fuel burn and emissions for years 2000 through 2004. These historical inventories were developed by modeling high-resolution gate-to-gate movements of all global commercial flights in each year. This report presents the inventory data in various forms and also provides derivative metrics and comparative assessments.

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LIST OF ACRONYMS

4D	Four-Dimensional
AEE	Office of Environment and Energy
BACK	BACK Aviation Solutions
BADA	Base of Aircraft Data
CAEP	Committee on Aviation Environmental Protection
CDA	Continuous Descent Approach
CNS	Communication, Navigation, and Surveillance
EDMS	Emissions and Dispersion Modeling System
EI	Emissions Index
ETMS	Enhanced Traffic Management System
Eurocontrol	European Organization for the Safety of Air Navigation
FAA	Federal Aviation Administration
GC	Great Circle
ICAO	International Civil Aviation Organization
LMI	Logistics Management Institute
LTO	Landing and Takeoff
NASA	National Aeronautics and Space Administration
OAG	Official Airline Guide
RVSM	Reduced Vertical Separation Minimum
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States

1 Introduction

The United States (US) Federal Aviation Administration (FAA) Office of Environment and Energy (AEE) developed the System for assessing Aviation's Global Emissions (SAGE) with support from the Volpe National Transportation Systems Center (Volpe), the Massachusetts Institute of Technology (MIT) and the Logistics Management Institute (LMI). SAGE is a high fidelity computer model used to predict aircraft fuel burn and emissions for all commercial (civil) flights globally in a given year. The model can analyze scenarios from a single flight to airport, country, regional, and global levels. In addition, SAGE dynamically models aircraft performance, fuel burn and emissions, capacity and delay at airports, and forecasts of future scenarios. The purpose of SAGE is to provide FAA, and indirectly the international aviation community, with a tool to evaluate the effects of various policy, technology, and operational scenarios on aircraft fuel use and emissions. Currently at Version 1.5, SAGE is not for use on a stand alone personal computer; it is an FAA government research tool, not for release to the public. However, results from the model have been made available to the international aviation community; and, FAA is committed to the continued development, support and reporting of SAGE.

SAGE Version 1.5 has been used to generate global inventories of fuel burn and emissions for years 2000 through 2004. These historical inventories were developed by modeling high-resolution gate-to-gate movements of all global commercial flights in each year. This report presents the inventory data in various forms and also provides derivative metrics and comparative assessments. As this report is intended to present inventory data, technical model details and validation assessments are not discussed. Such details can be found in FAA[a] 2005 and FAA[b] 2005.

The inventory data presented in this report represents condensed (e.g., aggregated) versions of the raw inventory outputs from SAGE which range from inventories with tens of millions of records to those with approximately a billion records of detailed flight results for each modeled year. Significant resources are expended in generating these raw inventories and the condensed, derived data.

As a formal disclaimer, any SAGE data including those contained in this report are made available to interested parties as is. FAA is not liable for any misunderstandings and misuses of the data. The user is solely responsible for any consequences arising from inappropriate application of the data.

1.1 Background

The development of SAGE was in part stimulated by the rapid growth in aviation and the need for better emissions modeling capabilities on a global level. According to the "Special Report on Aviation and the Global Atmosphere" by the Intergovernmental Panel on Climate Change (IPCC), air transportation accounted for 2 percent of all anthropogenic carbon dioxide emissions in 1992 and 13 percent of the fossil fuel used for transportation. In a 10-year period, passenger traffic on scheduled airlines grew by 60 percent; and, air travel was expected to increase by 5 percent for the next 10 to 15 years [IPCC 1999]. With this forecast, aircraft remain an important source of greenhouse gases in coming decades [IPCC 1999]. It was also estimated that in 1992, aircraft were responsible for 3.5 percent of all anthropogenic radiative forcing of the climate and (at the time of the report, were) expected to grow to as much as 12 percent by 2050 [IPCC 1999].

The Committee on Aviation Environmental Protection (CAEP) of the International Civil Aviation Organization (ICAO), an organization of the United Nations (UN), has formed several working groups to address aviation environmental emissions. In addition, the UN Framework Convention on Climate

Change (UNFCCC) has promoted a series of multilateral agreements that target values of emissions reductions for the primary industrialized nations [IPCC 1999]. However, prior to SAGE, there was no comprehensive, up-to-date, non-proprietary model to estimate aviation emissions at national or international levels that could be used for evaluating policy, technology and operational alternatives.

Although the degree of projected growth of the air transportation industry may be debated, the unique characteristics of the industry, the influence that they may have upon the environment, and the influence that policies may have upon the industry dictates a clear need for a computer model that analysts can use to predict and evaluate the effects of different policy, technology, and operational scenarios.

Past studies on aircraft emissions have resulted in global inventories of emissions by various organizations including the National Aeronautics and Space Administration (NASA)/Boeing [Baughcum 1996[a,b] and Sutkus 2001], Abatement of Nuisance Caused by Nuisances Caused by Air Transport (ANCAT)/European Commission (EC) 2 group [Gardner 1998], and Deutsche Forschungsanstalt fur Luft- and Raumfahrt (DLR) [Schmitt 1997]. These inventories represent significant accomplishments since they are the first set of "good-quality" global emissions estimates. In this light, SAGE represents the lessons learned from these past studies. Using the best publicly available data and methods, SAGE improves upon these past studies in producing the highest quality emissions inventories to date.

1.2 Objective and Scope

The objective for SAGE is to be an internationally accepted computer model that is based on the best publicly available data and methodologies, and that can be used to estimate the effects on global aircraft fuel burn and emissions from various policy, technology, and operational scenarios. With regard to scope, the model is capable of analyses from a single flight to airport, regional, and global levels of commercial (civil) flights on a worldwide basis.

1.3 Modeling Capabilities

With the computation modules and the supporting data integrated in a dynamic modeling environment, SAGE provides the capability to model changes to various parameters including those associated with flight schedules, trajectories, aircraft performance, airport capacities and delays, etc. This results in the ability to use SAGE for applications such as quantification of the effects of Communication, Navigation, and Surveillance (CNS)/Air Traffic Management (ATM) initiatives, determining the benefits of Reduced Vertical Separation Minimum (RVSM), investigation of trajectory optimizations, and computing potential emissions benefits from the use of a Continuous Descent Approach (CDA).

SAGE can generate inventories of fuel burn and emissions of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx), carbon dioxide (CO_2), water (H_2O), and sulfur oxides (SOx calculated as sulfur dioxide, SO_2). The three basic inventories generated by SAGE are: (1) four-dimensional (4D) variable world grids currently generated in a standardized 1^o latitude by 1^o longitude by 1 km altitude format; (2) modal results of each individual flight worldwide; and (3) individual chorded (flight segment) results for each flight worldwide. These outputs and the dynamic modeling environment allow for a comprehensive set of analyses that can be conducted using SAGE.

1.4 Document Outline

The remainder of this document is organized as follows. Section 2 defines and discusses the raw inventories generated by the model. This section serves as background material for the subsequent sections. Section 3 describes the various processed inventories which provide more meaningful information. Section 4 presents comparisons of SAGE data with those from past studies. Finally, Section 5 provides concluding remarks related to these inventories generated by SAGE Version 1.5.

2 Raw Inventory Descriptions

The basic outputs from SAGE are fuel burn and emissions of CO, HC, NOx, CO_2, H_2O, and SOx (modeled as SO_2). These data and others are generated by SAGE as part of three raw inventories as shown in Figure 1: (1) flight-level modal, (2) chord-level, and (3) 4D world grids.

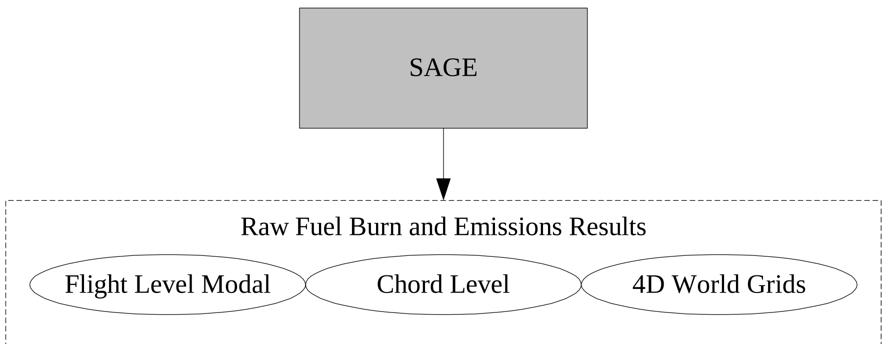

Figure 1. Raw and Processed Inventories

These three inventories are generated for each year and stored in a relational database (i.e., SQL database). Currently, inventories have been generated for five years: 2000 through 2004. Sections 2.1 through 2.3 describe each of these inventories. These descriptions are provided as background material and to serve as the basis for further discussions and presentations of the processed data in the ensuing sections.

2.1 Raw Flight-Level Modal Inventory

The flight-level modal inventory contains listings of each individual civil flight on a global basis. This inventory contains over 30 millions per year. These results are provided modally as indicated by the fields shown below:

- flight_key = unique SAGE flight key
- flight_date = flight departure date
- source_flag = E=Enhanced Traffic Management System (ETMS), O=Official Airline Guide (OAG)
- flight_id = flight ID
- status_flag = internal debugging flag
- dep_airport = departure airport code
- arr_airport = arrival airport code
- dep_time = departure time
- arr_time = arrival time
- cruise_altitude (ft) = cruise altitude
- track_no = dispersion track number for OAG flights
- aircraft_type = aircraft code

- aircraft_category = J=Jet, T=Turboprop, P=Piston
- num_engines = number of engines
- back_engine = BACK Aviation's Fleet data engine name/code
- icao_edms_engine = ICAO or FAA's Emissions and Dispersion Modeling System (EDMS) engine name/code
- gc_distance (nm) = Great Circle (GC) distance
- flight_distance (nm) = flight distance
- carrier_code = carrier code
- carrier_name = carrier name
- region_code = region code (8 world regions)
- region_name = region name (8 world regions)
- region_end_type = I=flight ended in same region, O=ended elsewhere
- dep_country = departure country name
- arr_country = arrival country name
- takeoff_weight (kg) = assigned takeoff weight
- scale_factor = scale factor for unscheduled flights
- dep_gnd_distance (nm) = departure ground distance
- dep_gnd_fuelburn (kg) = departure ground fuel burn
- dep_gnd_co2 (g) = departure ground CO_2
- dep_gnd_h2o (g) = departure ground H_2O
- dep_gnd_sox (g) = departure ground SOx
- dep_gnd_co (g) = departure ground CO
- dep_gnd_hc (g) = departure ground HC
- dep_gnd_nox (g) = departure ground NOx
- to_co_distance (nm) = takeoff/climbout distance
- to_co_fuelburn (kg) = takeoff/climbout fuel burn
- to_co_co2 (g) = takeoff/climbout CO_2
- to_co_h2o (g) = takeoff/climbout H_2O
- to_co_sox (g) = takeoff/climbout SOx
- to_co_co (g) = takeoff/climbout CO
- to_co_hc (g) = takeoff/climbout HC
- to_co_nox (g) = takeoff/climbout NOx
- cruise_distance (nm) = cruise distance
- cruise_fuelburn (kg) = cruise fuelf burn
- cruise_co2 (g) = cruise CO_2
- cruise_h2o (g) = cruise H_2O
- cruise_sox (g) = cruise SOx
- cruise_co (g) = cruise CO
- cruise_hc (g) = cruise HC
- cruise_nox (g) = cruise NOx
- app_glide_distance (nm) = approach distance
- app_glide_fuelburn (kg) = approach fuel burn
- app_glide_co2 (g) = approach CO_2
- app_glide_h2o (g) = approach H_2O

- app_glide_sox (g) = approach SOx
- app_glide_co (g) = approach CO
- app_glide_hc (g) = approach HC
- app_glide_nox (g) = approach NOx
- arr_gnd_distance (nm) = arrival ground distance
- arr_gnd_fuelburn (kg) = arrival ground fuel burn
- arr_gnd_co2 (g) = arrival ground CO_2
- arr_gnd_h2o (g) = arrival ground H_2O
- arr_gnd_sox (g) = arrival ground SOx
- arr_gnd_co (g) = arrival ground CO
- arr_gnd_hc (g) = arrival ground HC
- arr_gnd_nox (g) = arrival ground NOx
- fuelburn (kg) = total fuel burn
- co2 (g) = total CO_2
- h2o (g) = total H_2O
- sox (g) = total SOx
- co (g) = total CO
- hc (g) = total HC
- nox (g) = total NOx

Regarding the definition for modes, 3000 ft is used to differentiate cruise from takeoff/climbout and approach. This inventory provides enough details for most comparison and trend analyses by regional, country, airport, and aircraft levels.

Due to the large uncertainties associated with emissions indices (EI) for piston engines, flights with aircraft using piston engines have been flagged in this inventory. These flights are currently excluded when the data is used to generate more meaningful aggregated results (e.g., regional, country, etc. totals).

2.2 Raw Chord-Level Inventory

The chord-level inventory contains a listing of individual flight chords for all flights worldwide resulting in approximately 1 billion yearly records. Even though each listing represents a point in space geometrically, it can be considered to represent a chord (or segment) because much of the information provided in the inventory necessarily apply to the entire chord rather than just a point. For clarity, the ends of a chord are referred to as either the head (beginning) or tail (ending) points. And it should be obvious that the tail point of one chord represents the head point of the next chord. Whether the data in the inventory applies to a point or the entire chord, the information is always stored at the tail point of the chord. The fields within this inventory are provided as follows:

- flight_key = unique SAGE flight key
- seq_no = chord sequence number
- mode = mode number for chord
- latitude (deg) = latitude of chord tail
- longitude (deg) = longitude of chort tail
- altitude (m) = altitude of chord tail
- chord_time = point in time at chord tail
- T_i (K) = temperature at chord tail

- P_i (Pa) = pressure at chord tail
- a_i (m/s) = speed of sound at chord tail
- m_i = average Mach number for chord
- h_i (m) = average height of chord
- delta_alt (m) = change in altitude for chord
- v_i (m/s) = average speed of chord
- delta_v (m/s) = change in speed for chord
- delta_t (s) = change in time for chord
- distance (nm) = length of chord
- thrust (N) = thrust for the chord
- weight (kg) = aircraft weight at chord tail
- cl_i = Eurocontrol's Base of Aircraft data (BADA) lift coefficient for chord
- cd_i = BADA drag coefficient for chord
- l_i (N) = lift force for chord
- d_i (N) = drag force for chord
- f_i (kg/s) = fuel flow for chord
- percent_foo = percent power for chord
- reico_i (g/kg-fuel) = corrected (reference) CO emissions index (EI) for chord
- reihc_i (g/kg-fuel) = corrected (reference) HC EI for chord
- reinox_i (g/kg-fuel) = corrected (reference) NOx EI for chord
- fuelburn (kg) = fuel burned for chord
- co2 (g) = CO_2 emitted for chord
- h2o (g) = H_2O emitted for chord
- sox (g) = SOx emitted for chord
- co (g) = CO emitted for chord
- hc (g) = HC emitted for chord
- nox (g) = NOx emitted for chord

This inventory has typically been used for model improvements, validation, and detailed scenario modeling, especially those involving modifications to aircraft performance parameters.

2.3 Raw 4D World Gridded Inventory

The 4D world grid inventory contains a listing of flight segments similar to the chord-level inventory but the segments correspond to the portions of the chords that traversed a grid. The data is 4D since each segment listing contains flight date/time and grid location information. The similarity to the chord-level inventory is reflected by the approximately 900 million yearly records within this inventory. The fields in the inventory are shown below:

- flight_key = unique SAGE flight key
- flight_date = departure date
- track_id = dispersion track number for OAG flights
- seq_no = chord sequence number
- mode = mode number
- i = latitude index
- j = longitude index
- k = altitude index

- time_in = time entered into grid
- deltat_i (s) = duration in grid
- v_i (m/s) = average speed of chord
- fuelburn (kg) = fuel burned while in grid
- co2 (g) = CO_2 emitted while in grid
- h2o (g) = H_2O emitted while in grid
- co (g) = CO emitted while in grid
- sox (g) = SOx emitted while in grid
- hc (g) = HC emitted while in grid
- nox (g) = NOx emitted while in grid

The current standard grid size is 1^o latitude by 1^o longitude by 1 km altitude. But these specifications can be modified to obtain varying sizes in all three dimensions. The i, j, and k indices used in this inventory are based on the standard grid cell size, and their orientation is shown in Figure 2.

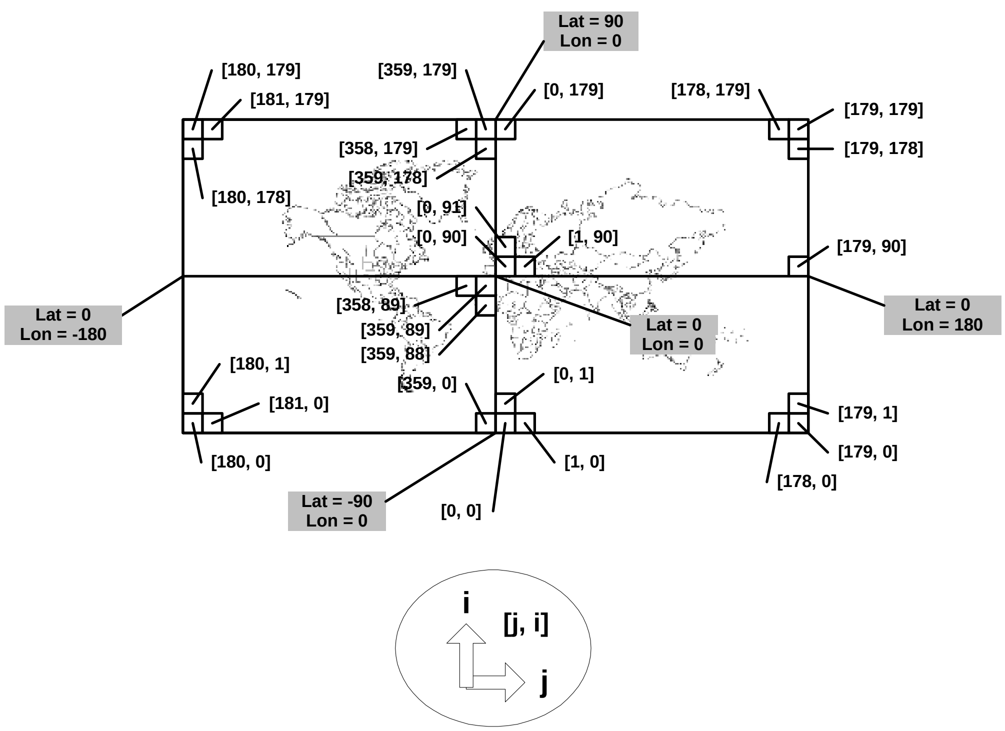

Figure 2. Orientation of Standard Grids within SAGE

This inventory provides the data necessary to assess the spatial and temporal distributions of fuel burn and emissions. The potential exists for the data to serve as inputs to atmospheric dispersion and global warming models.

3 Processed Inventories

Since the raw inventories have been stored in a relational database, they can be easily queried to generate various derivative inventories. These "processed" inventories are the results of further categorizations, aggregations, and computations using the raw data. Overall, the global fuel burn and emissions totals are presented in Table 1.

Table 1. Yearly Global Total Fuel Burn and Emissions

Year	Flights	Distance (nm)	Fuel Burn (Tg)	NOx (Tg)	CO (Tg)	HC (Tg)	CO_2 (Tg)	H_2O (Tg)	SOx (Tg)
2000	29706287	1.80E+10	181	2.51	0.541	0.0757	572	224	0.145
2001	27673927	1.72E+10	170	2.35	0.464	0.0630	536	210	0.136
2002	28477399	1.76E+10	171	2.41	0.480	0.0639	539	211	0.137
2003	28780037	1.86E+10	176	2.49	0.486	0.0617	557	218	0.141
2004	30378593	2.00E+10	188	2.69	0.511	0.0625	594	233	0.151

In general, as more fuel is burned, more emissions are likely to be generated as well. As expected, emissions of CO_2, H_2O, and SOx follow the exact same yearly trend as fuel burn since they are modeled strictly based on fuel composition assuming 100% combustion of the fuel. NOx also follows fuel burn changes closely but less than the aforementioned pollutants due to some non-linear effects. CO and HC follow fuel burn the least due to stronger non-linear effects. Some corresponding fuel burn and emissions metrics are provided in Table 2.

Table 2. Yearly Global Derived Metrics of Fuel Efficiency and Emissions Indices

Year	Fuel Burn per Distance (Tg/Billion km)	EI NOx (g/kg)	EI CO (g/kg)	EI HC (g/kg)	EI CO_2 (g/kg)	EI H_2O (g/kg)	EI SOx (g/kg)
2000	5.43	13.8	2.98	0.417	3155	1237	0.8
2001	5.33	13.8	2.73	0.371	3155	1237	0.8
2002	5.23	14.1	2.81	0.374	3155	1237	0.8
2003	5.12	14.1	2.76	0.350	3155	1237	0.8
2004	5.08	14.3	2.71	0.332	3155	1237	0.8

The fuel efficiency metric (i.e., fuel burn per distance) indicates that there may be a global increase in efficiency as less fuel appears to be used per distance flown. Although some trends may appear to be present with regards to the emissions indices for NOx, CO, and HC, consideration of non-linear effects would make any conclusions difficult. The emissions indices for CO_2, H_2O, and SOx are constants due to the aforementioned modeling based strictly on fuel composition. The global modal splits of fuel burn and NOx emissions are presented in Table 3.

Table 3. Landing and Takeoff (LTO) and Cruise Fuel Burn and NOx Emissions

	Fuel Burn (Tg)		NOx (Tg)	
Year	LTO	Cruise	LTO	Cruise
2000	12.9	168	0.197	2.31
2001	12.3	158	0.191	2.16
2002	12.2	159	0.194	2.22
2003	12.4	164	0.199	2.29
2004	12.9	175	0.210	2.48

As discussed in Section 2.1, 3000 ft altitude is used to differentiate between the landing and takeoff (LTO) cycle and cruise. Specifically, the definition for the LTO cycle category is all fuel burn and emissions generated equal to or below 3000 ft above airport field elevation (AFE). Consequently, cruise is defined as all fuel burn and emissions generated above 3000 ft AFE. Since NOx tends to follow fuel burn trends well, the cruise to LTO ratios are both similar for fuel burn (about 13) and NOx (about 11.5). These ratios are approximately constant for each of the five years.

The global fuel burn and emissions separated into jet and turboprop categories are shown in Table 4.

Table 4. Global Fuel Burn and NOx Emissions Separated into Jet and Turboprop categories.

	Fuel Burn (Tg)		NOx (Tg)	
Year	Jet	Turboprop	Jet	Turboprop
2000	177	4.25	2.45	0.0569
2001	166	3.48	2.30	0.0486
2002	167	3.51	2.37	0.0485
2003	173	3.28	2.45	0.0470
2004	185	3.28	2.64	0.0468

As discussed in Section 2.1, the turboprop category does not include piston-powered aircraft as these have been excluded due to the uncertainties associated with their emissions data. As expected, the jet contribution to global fuel burn and NOx emissions is far greater than turboprops due to the greater number of jet operations as well as the higher fuel burn on a per flight basis. Similar to the cruise and LTO comparisons, the jet to turboprop ratio is also similar when comparing fuel burn and NOx. However, the ratios appear to be different from year to year. The ratios increase from about 42-43 to about 56, possibly indicating an increase in jet usage or a decrease in turboprop usage.

3.1 Regional and Country Inventories

The SAGE flight-level modal inventory was processed to derive regional and country inventories. The attribution of fuel burn and emissions to a region or country is mainly based on the location (or ownership) of the departure airport. Figure 3 shows a plot to illustrate the worldwide locations of airports color-coded by region.

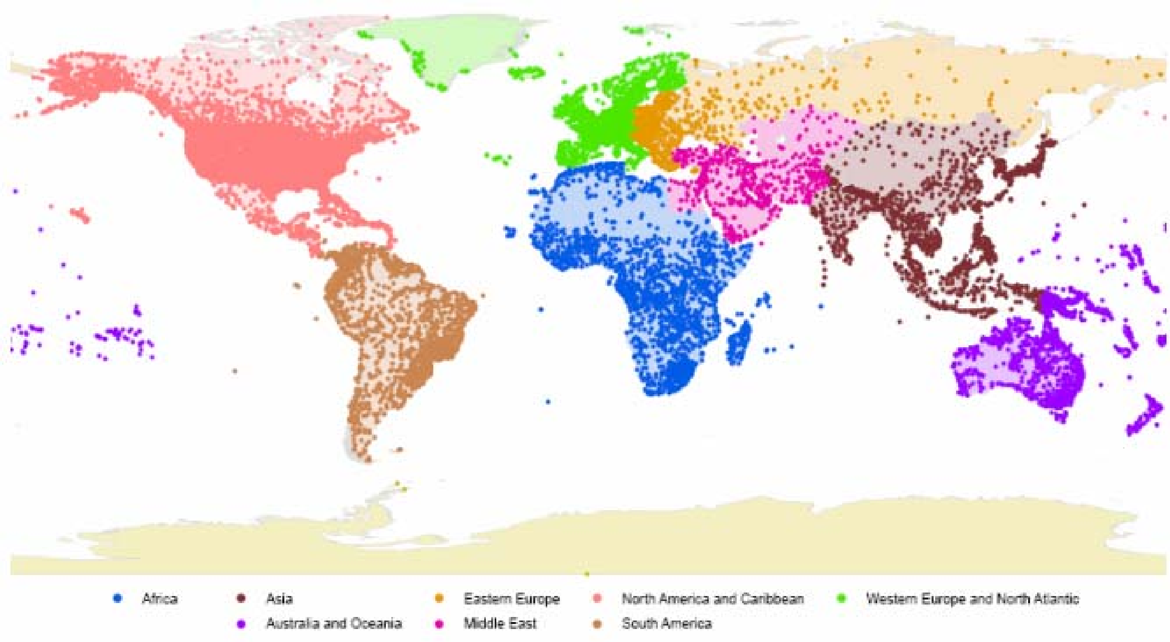

Figure 3. Worldwide Airport Locations Color-Coded by Region

All fuel burn and emissions for a flight are attributed to the country/region containing the airport and is either categorized as domestic or international depending on whether or not the arrival airport is within the same country/region. The following examples illustrate this definition:

- Flight 1: Country A, Domestic
  - Departure airport in country A
  - Arrival airport in country A

- Flight 2: Country A, International
  - Departure airport in country A
  - Arrival airport in country B

The fuel burn and emissions resulting from flight 1 are attributed to the country A, domestic category because both the departure and arrival airports are in country A. In contrast, the fuel burn and emissions for flight 2 are categorized into the country A, international category because the arrival airport is not within country A. That is, any country other than A would result in the same international classification. In accordance with the terminology often used by UNFCCC, the international category can also be referred to as a "bunker" category [IPCC 1997].

As indicated in Figure 3, the SAGE data are typically aggregated into the following eight world regions:

- Africa
- Asia
- Australia and Oceania
- Eastern Europe
- Middle East
- North America and Caribbean
- South America
- Western Europe and North Atlantic

The allocation of countries to each of these regions can be found in FAA[a] 2005. The regional inventories subdivided into domestic versus international and modal categories for 2000 to 2004 are provided in Appendix A. Based on this data, the yearly regional totals for fuel burn and NOx are presented in Tables 4 and 5 with corresponding plots shown in Figures 4 through 7.

Table 5. Yearly Regional Totals for Fuel Burn (Tg)

Type	Region	2000	2001	2002	2003	2004
Domestic	Africa	1.12	1.15	1.14	1.19	1.25
	Asia	16.8	17.7	18.4	19.2	21.3
	Australia and Oceania	2.39	2.44	2.29	2.12	2.31
	Eastern Europe	1.88	2.03	2.04	2.26	2.45
	Middle East	2.46	2.39	2.37	2.57	2.83
	North America and Caribbean	62.9	57.4	55.1	56.1	56.5
	South America	3.27	3.41	3.40	3.06	3.21
	Western Europe and North Atlantic	13.6	12.7	13.9	15.3	16.1
International	Africa	2.42	2.38	2.56	2.64	2.86
	Asia	15.9	15.2	15.4	15.8	17.5
	Australia and Oceania	2.86	2.62	2.66	2.72	3.15
	Eastern Europe	2.06	2.01	2.09	2.39	2.81
	Middle East	5.08	4.98	4.81	5.40	6.45
	North America and Caribbean	22.7	18.2	19.7	19.9	21.3
	South America	3.31	2.98	3.02	2.80	3.20
	Western Europe and North Atlantic	22.6	22.2	21.9	23.0	25.2
Global Total	N/A	181	170	171	176	188

Table 6. Yearly Regional Totals for NOx Emissions (Tg)

Type	Region	2000	2001	2002	2003	2004
Domestic	Africa	0.0140	0.0142	0.0140	0.0146	0.0153
	Asia	0.263	0.277	0.285	0.295	0.333
	Australia and Oceania	0.0337	0.0328	0.0308	0.0301	0.0332
	Eastern Europe	0.0165	0.0175	0.0172	0.0186	0.0193
	Middle East	0.0381	0.0379	0.0380	0.0413	0.0458
	North America and Caribbean	0.786	0.716	0.708	0.717	0.724
	South America	0.0379	0.0393	0.0424	0.0386	0.0409
	Western Europe and North Atlantic	0.167	0.159	0.178	0.196	0.210
International	Africa	0.0353	0.0350	0.0393	0.0405	0.0440
	Asia	0.243	0.231	0.240	0.246	0.272
	Australia and Oceania	0.0455	0.0421	0.0424	0.0432	0.0502
	Eastern Europe	0.0236	0.0230	0.0244	0.0287	0.0341
	Middle East	0.0730	0.0732	0.0710	0.0792	0.0963
	North America and Caribbean	0.341	0.273	0.305	0.311	0.334
	South America	0.0466	0.0432	0.0435	0.0402	0.0466
	Western Europe and North Atlantic	0.342	0.335	0.335	0.353	0.387
Global Total	N/A	2.51	2.35	2.41	2.49	2.69

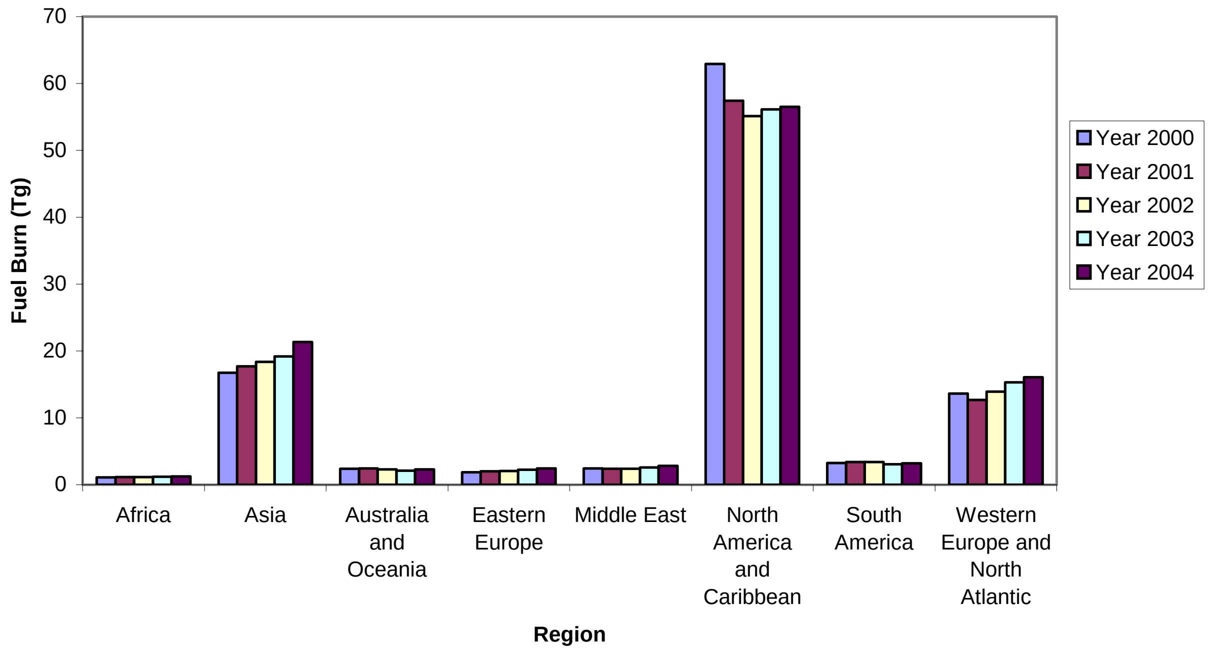

Figure 4. Comparison of Regional Domestic Fuel Burn

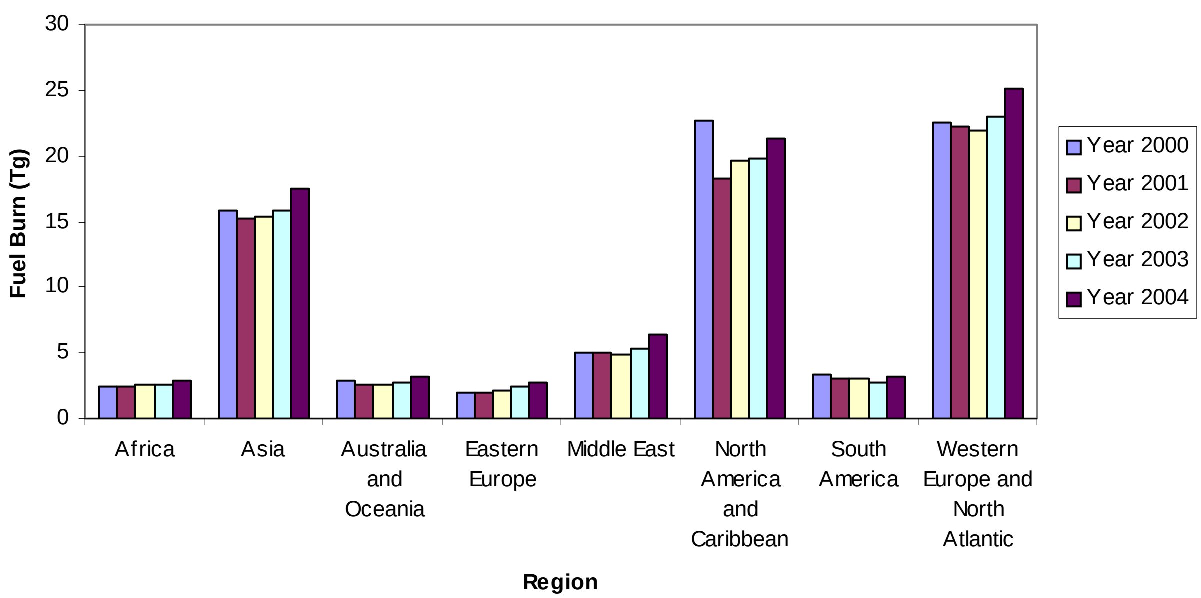

Figure 5. Comparison of Regional International Fuel Burn

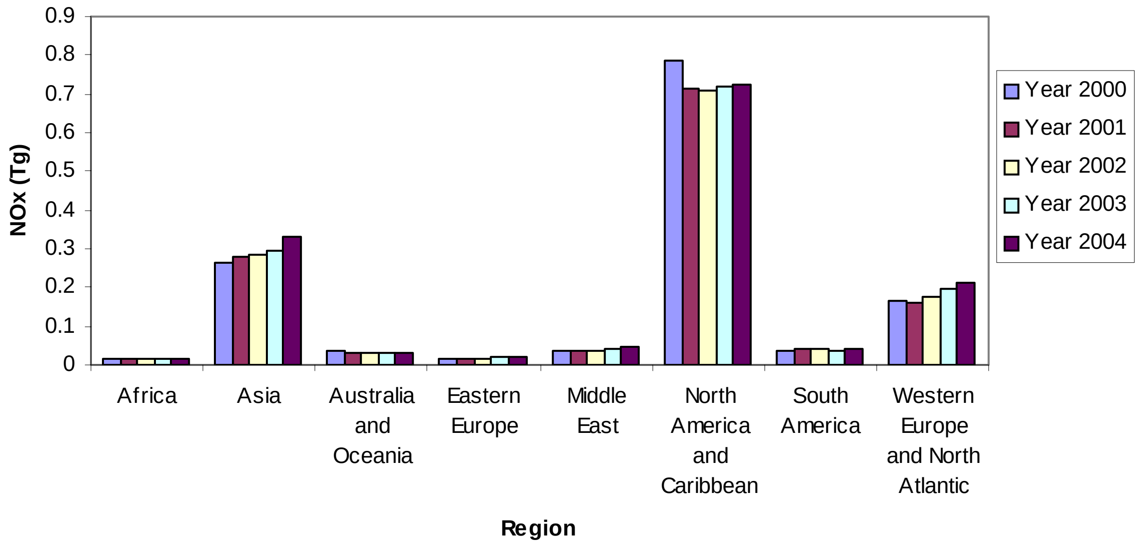

Figure 6. Comparison of Regional Domestic NOx Emissions

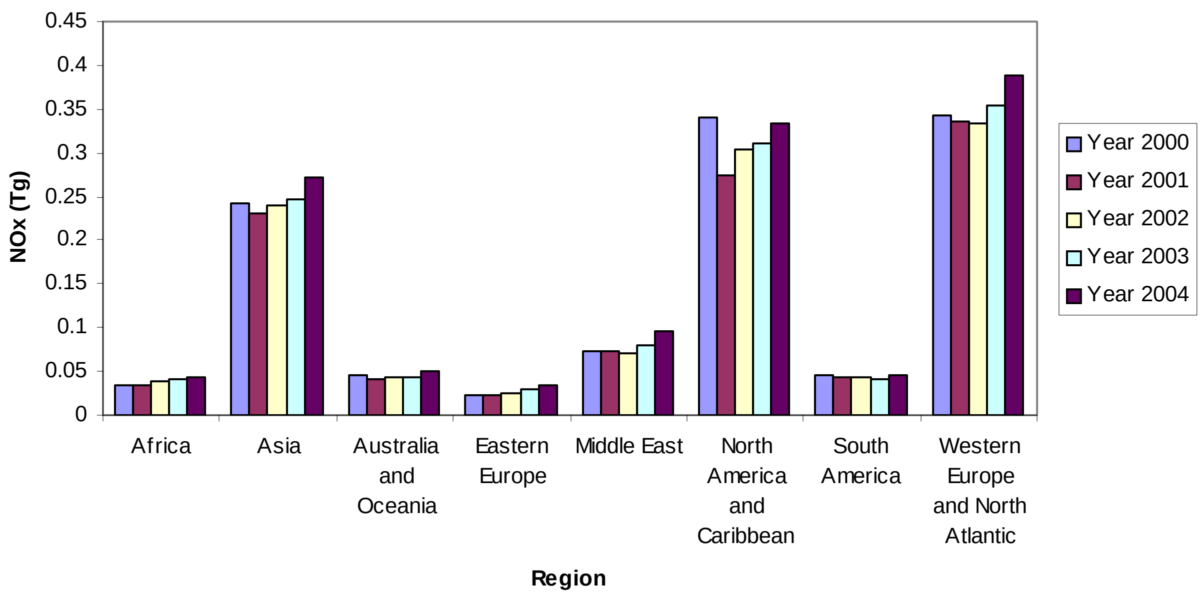

Figure 7. Comparison of Regional International NOx Emissions

The comparisons in Figures 4 and 5 show that global domestic fuel burn is dominated by the North America and Caribbean region. In contrast, international fuel burn is similar among three regions: Asia, North America and Caribbean, and Western Europe and North Atlantic. The yearly trends in each of these regions generally show an increase from 2002 to 2004 to reflect the growth in the aviation industry. However, decreases shown from 2000 to the following years reflect the effects of September 11, 2001. As expected, the NOx comparisons shown in Figures 6 and 7 follow the same type of distributions as shown by the fuel burn comparisons. A couple of normalized fuel burn and NOx metrics (i.e., per distance and per NOx) are shown in Tables 7 through 10.

Table 7. Regional Fuel Burn per Distance (Tg/Billion km)

Type	Region	2000	2001	2002	2003	2004
Domestic	Africa	4.24	3.95	3.87	3.77	3.73
	Asia	6.45	6.36	6.21	6.06	5.86
	Australia and Oceania	3.86	3.87	3.91	3.88	3.85
	Eastern Europe	5.22	5.15	5.02	5.01	5.00
	Middle East	5.91	5.98	6.02	6.09	6.06
	North America and Caribbean	4.07	3.94	3.78	3.65	3.53
	South America	3.94	3.93	4.02	4.17	4.19
	Western Europe and North Atlantic	3.68	3.63	3.58	3.56	3.57
International	Africa	8.05	8.01	8.02	7.65	7.33
	Asia	10.60	10.49	10.38	10.20	9.99
	Australia and Oceania	9.33	9.41	8.77	8.71	8.63
	Eastern Europe	4.52	4.39	4.38	4.32	4.23
	Middle East	7.05	7.10	6.98	6.98	7.06
	North America and Caribbean	8.76	8.66	8.77	8.74	8.67
	South America	7.07	7.02	6.93	6.78	6.88
	Western Europe and North Atlantic	8.09	8.09	8.03	7.90	7.74

Table 8. Regional Fuel Burn per Flight (Mg/Flight)

Type	Region	2000	2001	2002	2003	2004
Domestic	Africa	2.99	2.80	2.83	2.87	2.89
	Asia	6.22	6.26	6.21	6.25	6.33
	Australia and Oceania	2.85	2.99	2.97	2.99	3.06
	Eastern Europe	5.17	5.07	5.10	5.24	5.10
	Middle East	4.79	4.82	5.03	5.26	5.41
	North America and Caribbean	3.82	3.89	3.68	3.74	3.62
	South America	2.86	2.89	2.91	3.20	3.31
	Western Europe and North Atlantic	2.56	2.59	2.59	2.71	2.74
International	Africa	31.8	31.0	30.6	28.9	27.8
	Asia	72.7	74.5	71.4	69.6	68.1
	Australia and Oceania	51.5	58.7	48.7	49.1	50.0
	Eastern Europe	7.62	7.21	7.28	7.36	7.11
	Middle East	23.5	23.6	23.2	23.4	24.3
	North America and Caribbean	57.1	57.7	57.0	57.9	58.0
	South America	31.9	34.0	31.3	31.8	33.5
	Western Europe and North Atlantic	35.1	34.5	33.9	32.6	31.0

Table 9. Regional NOx Emissions per Distance (Tg/Billion km)

Type	Region	2000	2001	2002	2003	2004
Domestic	Africa	0.0531	0.0490	0.0476	0.0465	0.0457
	Asia	0.101	0.0996	0.0964	0.0931	0.0915
	Australia and Oceania	0.0544	0.0519	0.0525	0.0550	0.0555
	Eastern Europe	0.0458	0.0443	0.0424	0.0412	0.0393
	Middle East	0.0915	0.0947	0.0964	0.0978	0.0980
	North America and Caribbean	0.0508	0.0492	0.0485	0.0466	0.0452
	South America	0.0457	0.0453	0.0501	0.0528	0.0535
	Western Europe and North Atlantic	0.0451	0.0454	0.0458	0.0457	0.0468
International	Africa	0.118	0.118	0.123	0.117	0.113
	Asia	0.162	0.160	0.161	0.158	0.155
	Australia and Oceania	0.149	0.151	0.140	0.138	0.138
	Eastern Europe	0.0520	0.0503	0.0511	0.0517	0.0512
	Middle East	0.101	0.104	0.103	0.103	0.105
	North America and Caribbean	0.132	0.130	0.136	0.137	0.136
	South America	0.100	0.102	0.100	0.0974	0.1004
	Western Europe and North Atlantic	0.122	0.122	0.123	0.121	0.119

Table 10. Regional NOx Emissions per Flight (Kg/Flight)

Type	Region	2000	2001	2002	2003	2004
Domestic	Africa	37.4	34.7	34.9	35.4	35.3
	Asia	97.4	98.0	96.3	96.0	98.7
	Australia and Oceania	40.1	40.1	40.0	42.3	44.1
	Eastern Europe	45.3	43.7	43.0	43.1	40.1
	Middle East	74.1	76.3	80.6	84.5	87.5
	North America and Caribbean	47.7	48.4	47.3	47.8	46.4
	South America	33.2	33.3	36.3	40.5	42.3
	Western Europe and North Atlantic	31.5	32.4	33.1	34.8	35.8
International	Africa	465	456	470	443	427
	Asia	1110	1140	1110	1080	1060
	Australia and Oceania	822	943	778	779	797
	Eastern Europe	87.6	82.5	84.9	88.1	86.2
	Middle East	338	346	342	343	363
	North America and Caribbean	859	865	882	906	911
	South America	449	492	452	456	489
	Western Europe and North Atlantic	531	521	519	501	477

Tables 7 and 9 indicate that the international fuel burn and NOx emissions per distance values are generally larger than the domestic values by a factor of about 2 but as much as 3. Also, the international per flight values are larger than the domestic counterparts by about a magnitude. Although there may be several reasons for this, the most likely is due to the fact that the longer, international flights tend to use larger and greater fuel-consuming aircraft than the shorter domestic flights.

Similar to these regional inventories, country inventories have also been generated for all countries worldwide. Since the data is too numerous to present in this report, inventories for a selected group of 29 mostly modernized countries are provided in Appendix B. The selected countries are listed below:

- Australia
- Austria
- Belarus
- Belgium
- Bulgaria
- Canada
- Croatia
- Czech Republic
- Denmark
- Finland
- France
- Germany
- Greece
- Hungary
- Iceland
- Ireland
- Italy
- Japan
- Latvia
- Netherlands
- New Zealand
- Norway
- Poland
- Portugal
- Spain
- Sweden
- Switzerland
- UK
- US

These 29 countries coincide with those for which fuel burn and emissions inventories were provided to the United Nations Framework Convention on Climate Change (UNFCCC). A summary of the domestic and international fuel burn and NOx emissions are provided in Tables 11 and 12.

Table 11. Yearly Total Fuel Burn by Country (Gg)

Type	Country	2000	2001	2002	2003	2004
Domestic	Australia	1.50E+03	1.65E+03	1.52E+03	1.29E+03	1.39E+03
	Austria	8.30E+00	6.90E+00	7.43E+00	7.50E+00	6.90E+00
	Belarus	0	2.13E-01	1.51E-01	3.64E-01	6.32E-02
	Belgium	0	0	0	0	0
	Bulgaria	1.23E+01	6.68E+00	5.09E+00	2.37E+00	1.72E+00
	Canada	2.45E+03	1.99E+03	2.10E+03	2.11E+03	2.19E+03
	Croatia	7.83E+00	8.40E+00	8.71E+00	8.93E+00	9.32E+00
	Czech Republic	1.14E+00	1.07E+00	1.04E+00	1.05E+00	1.15E+00
	Denmark	2.09E+01	2.18E+01	1.99E+01	1.87E+01	1.36E+01
	Finland	1.02E+02	9.88E+01	8.77E+01	8.44E+01	9.15E+01

	France	8.43E+02	8.05E+02	7.06E+02	6.51E+02	6.16E+02
	Germany	5.69E+02	5.47E+02	5.21E+02	5.23E+02	5.23E+02
	Greece	1.19E+02	1.23E+02	9.82E+01	9.82E+01	1.14E+02
	Hungary	0	0	0	0	0
	Iceland	7.10E+00	4.69E+00	4.36E+00	4.66E+00	5.25E+00
	Ireland	1.25E+01	1.13E+01	9.94E+00	9.84E+00	9.25E+00
	Italy	8.09E+02	7.75E+02	7.75E+02	8.17E+02	8.03E+02
	Japan	3.18E+03	3.25E+03	3.25E+03	3.38E+03	3.22E+03
	Latvia	0	0	0	0	0
	Netherlands	1.98E+00	1.79E+00	1.62E+00	1.34E+00	1.41E+00
	New Zealand	1.89E+02	1.73E+02	1.64E+02	1.79E+02	1.85E+02
	Norway	3.38E+02	3.06E+02	2.64E+02	2.80E+02	2.75E+02
	Poland	1.09E+01	1.31E+01	1.33E+01	1.36E+01	1.44E+01
	Portugal	6.62E+01	6.80E+01	7.95E+01	7.38E+01	7.15E+01
	Spain	8.75E+02	8.69E+02	7.94E+02	8.37E+02	9.04E+02
	Sweden	2.49E+02	2.34E+02	2.00E+02	1.96E+02	2.10E+02
	Switzerland	1.98E+01	1.73E+01	1.34E+01	1.24E+01	1.01E+01
	United Kingdom	6.09E+02	4.33E+02	6.75E+02	7.69E+02	8.14E+02
	United States of America	5.21E+04	4.81E+04	4.53E+04	4.60E+04	4.59E+04
International	Australia	2.28E+03	2.27E+03	2.06E+03	2.12E+03	2.48E+03
	Austria	4.81E+02	4.52E+02	4.60E+02	4.98E+02	5.93E+02
	Belarus	1.66E+01	1.99E+01	1.89E+01	1.96E+01	2.29E+01
	Belgium	1.23E+03	1.12E+03	8.52E+02	8.47E+02	8.87E+02
	Bulgaria	4.68E+01	5.39E+01	6.01E+01	6.73E+01	7.84E+01
	Canada	3.02E+03	2.56E+03	2.65E+03	2.62E+03	2.84E+03
	Croatia	3.12E+01	3.19E+01	3.14E+01	3.33E+01	3.41E+01
	Czech Republic	1.37E+02	1.35E+02	1.46E+02	1.79E+02	2.44E+02
	Denmark	6.13E+02	6.12E+02	5.98E+02	6.08E+02	6.66E+02
	Finland	3.02E+02	2.94E+02	3.04E+02	3.31E+02	3.80E+02
	France	4.43E+03	4.42E+03	4.39E+03	4.38E+03	4.72E+03
	Germany	5.67E+03	5.57E+03	5.56E+03	5.91E+03	6.35E+03
	Greece	5.20E+02	4.82E+02	5.47E+02	6.05E+02	7.05E+02
	Hungary	1.55E+02	1.49E+02	1.32E+02	1.45E+02	1.84E+02
	Iceland	1.03E+02	7.32E+01	7.47E+01	8.16E+01	1.01E+02
	Ireland	4.46E+02	3.98E+02	5.04E+02	5.62E+02	5.87E+02
	Italy	2.16E+03	2.02E+03	1.95E+03	2.15E+03	2.34E+03
	Japan	7.25E+03	6.81E+03	6.67E+03	6.75E+03	6.95E+03
	Latvia	1.84E+01	1.87E+01	1.78E+01	1.67E+01	3.51E+01
	Netherlands	2.67E+03	2.73E+03	2.77E+03	2.87E+03	3.12E+03
	New Zealand	5.00E+02	5.11E+02	5.23E+02	5.70E+02	6.55E+02
	Norway	2.30E+02	2.03E+02	2.02E+02	2.18E+02	2.61E+02
	Poland	1.68E+02	1.91E+02	1.68E+02	1.67E+02	1.97E+02
	Portugal	5.04E+02	4.81E+02	5.52E+02	5.85E+02	6.54E+02
	Spain	2.24E+03	2.14E+03	2.63E+03	2.93E+03	3.21E+03
	Sweden	5.03E+02	4.67E+02	4.40E+02	4.73E+02	5.28E+02
	Switzerland	1.45E+03	1.42E+03	1.27E+03	1.17E+03	1.12E+03
	United Kingdom	8.33E+03	7.93E+03	8.62E+03	9.79E+03	1.08E+04
	United States of America	2.20E+04	1.81E+04	1.92E+04	1.94E+04	2.04E+04

Table 12. Yearly Total NOx Emissions by Country (Gg)

Type	Country	2000	2001	2002	2003	2004
Domestic	Australia	2.11E+01	2.17E+01	2.00E+01	1.83E+01	1.99E+01
	Austria	1.01E-01	8.34E-02	8.80E-02	9.05E-02	8.37E-02
	Belarus	0	7.39E-03	2.46E-03	4.42E-03	7.67E-04
	Belgium	0	0	0	0	0
	Bulgaria	2.85E-01	2.00E-01	1.39E-01	1.08E-01	4.19E-02
	Canada	2.96E+01	2.41E+01	2.54E+01	2.52E+01	2.62E+01
	Croatia	1.37E-01	1.48E-01	1.51E-01	1.55E-01	1.60E-01
	Czech Republic	2.18E-02	1.28E-02	1.19E-02	1.31E-02	1.31E-02
	Denmark	2.71E-01	2.69E-01	2.49E-01	2.77E-01	1.86E-01
	Finland	1.34E+00	1.30E+00	1.19E+00	1.18E+00	1.26E+00
	France	1.11E+01	1.12E+01	9.93E+00	9.30E+00	9.06E+00
	Germany	7.86E+00	7.56E+00	7.18E+00	6.96E+00	7.26E+00
	Greece	1.55E+00	1.58E+00	1.32E+00	1.31E+00	1.55E+00
	Hungary	0	0	0	0	0
	Iceland	8.92E-02	6.61E-02	6.15E-02	6.96E-02	7.75E-02
	Ireland	2.04E-01	1.87E-01	1.54E-01	1.50E-01	1.49E-01
	Italy	9.75E+00	9.44E+00	9.51E+00	9.85E+00	9.74E+00
	Japan	5.70E+01	5.69E+01	5.71E+01	5.82E+01	5.61E+01
	Latvia	0	0	0	0	0
	Netherlands	2.22E-02	1.99E-02	1.74E-02	1.57E-02	1.92E-02
	New Zealand	2.39E+00	2.33E+00	2.39E+00	2.61E+00	2.73E+00
	Norway	4.51E+00	4.12E+00	3.58E+00	3.76E+00	3.82E+00
	Poland	1.46E-01	1.80E-01	1.79E-01	1.97E-01	2.08E-01
	Portugal	9.63E-01	1.01E+00	1.19E+00	1.05E+00	1.03E+00
	Spain	1.10E+01	1.14E+01	1.03E+01	1.10E+01	1.22E+01
	Sweden	3.24E+00	3.37E+00	2.96E+00	2.76E+00	2.79E+00
	Switzerland	2.82E-01	2.58E-01	2.46E-01	2.05E-01	1.58E-01
	United Kingdom	8.36E+00	5.74E+00	9.25E+00	1.07E+01	1.17E+01
	United States of America	6.57E+02	6.05E+02	5.86E+02	5.91E+02	5.93E+02
International	Australia	3.66E+01	3.60E+01	3.33E+01	3.41E+01	3.99E+01
	Austria	6.38E+00	6.26E+00	6.61E+00	7.12E+00	8.47E+00
	Belarus	1.61E-01	1.97E-01	2.15E-01	2.32E-01	3.58E-01
	Belgium	1.63E+01	1.47E+01	1.10E+01	1.09E+01	1.16E+01
	Bulgaria	4.33E-01	4.87E-01	6.14E-01	7.39E-01	8.63E-01
	Canada	4.19E+01	3.47E+01	3.74E+01	3.72E+01	3.97E+01
	Croatia	4.35E-01	4.36E-01	4.10E-01	4.47E-01	4.60E-01
	Czech Republic	1.59E+00	1.52E+00	1.68E+00	2.08E+00	2.93E+00
	Denmark	7.62E+00	7.68E+00	8.09E+00	8.36E+00	9.30E+00
	Finland	3.55E+00	3.49E+00	3.79E+00	4.18E+00	4.91E+00
	France	6.49E+01	6.65E+01	6.65E+01	6.63E+01	7.22E+01
	Germany	7.90E+01	7.94E+01	7.98E+01	8.46E+01	9.04E+01
	Greece	6.73E+00	6.31E+00	7.25E+00	7.94E+00	9.31E+00
	Hungary	1.68E+00	1.57E+00	1.41E+00	1.56E+00	2.02E+00
	Iceland	1.18E+00	7.58E-01	7.87E-01	8.81E-01	1.07E+00
	Ireland	5.89E+00	5.32E+00	6.81E+00	7.50E+00	8.02E+00
	Italy	2.90E+01	2.68E+01	2.57E+01	2.90E+01	3.30E+01
	Japan	1.10E+02	1.04E+02	1.02E+02	1.04E+02	1.09E+02

Latvia	2.06E-01	2.14E-01	1.90E-01	1.84E-01	3.85E-01
Netherlands	3.76E+01	3.88E+01	3.92E+01	4.10E+01	4.58E+01
New Zealand	7.73E+00	7.59E+00	7.63E+00	8.28E+00	9.94E+00
Norway	2.72E+00	2.38E+00	2.43E+00	2.69E+00	3.31E+00
Poland	1.94E+00	2.20E+00	1.96E+00	1.93E+00	2.24E+00
Portugal	6.52E+00	6.42E+00	7.47E+00	7.75E+00	8.85E+00
Spain	2.91E+01	2.89E+01	3.55E+01	3.89E+01	4.33E+01
Sweden	6.18E+00	5.80E+00	5.51E+00	6.63E+00	7.69E+00
Switzerland	2.03E+01	2.06E+01	1.82E+01	1.69E+01	1.58E+01
United Kingdom	1.28E+02	1.19E+02	1.33E+02	1.51E+02	1.67E+02
United States of America	3.23E+02	2.65E+02	2.91E+02	2.96E+02	3.15E+02

Inventory data such as that presented in Tables 11 and 12 can be used to satisfy, in part, the UNFCCC charge "to develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…" [UNEP/WMO 2000].

These yearly inventories show a noticeable decrease in fuel burn and NOx emissions from 2000 to 2001, mostly likely due to the events of September 11, 2001 (9/11). Although there is no clear trend for all countries, most of the larger countries appear to show a general trend toward increases in fuel burn and emissions after 2001. To illustrate this, fuel burn trends for ten of the larger countries is shown in Figures 8 through 10.

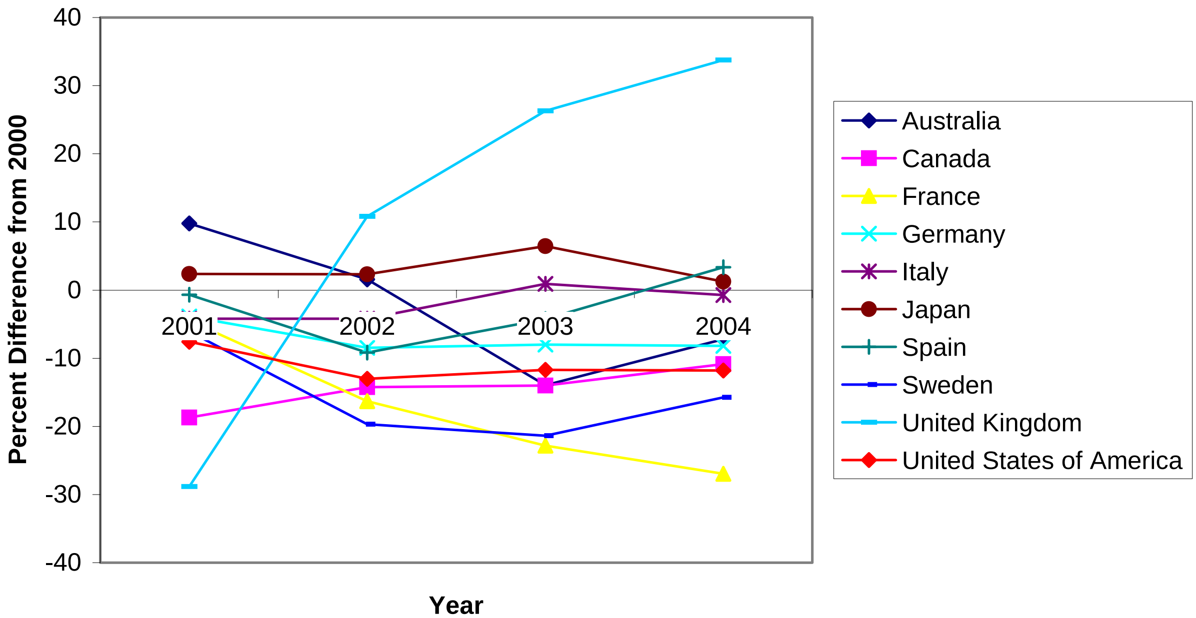

Figure 8. Trends in Domestic Fuel Burn for Selected Countries

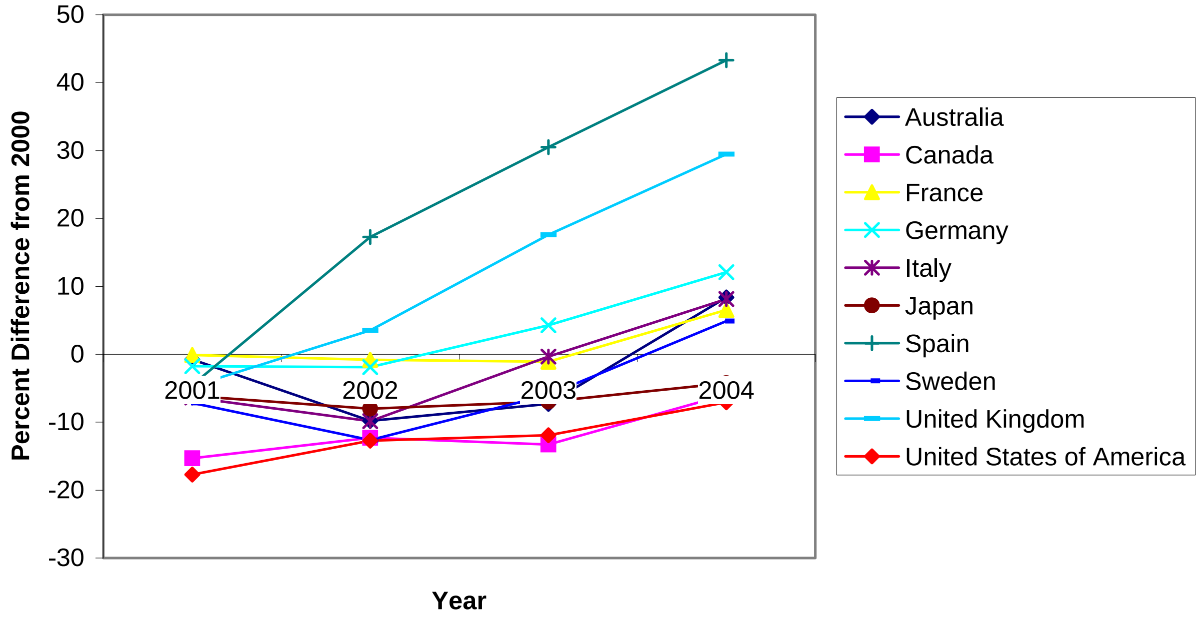

Figure 9. Trends in International Fuel Burn for Selected Countries

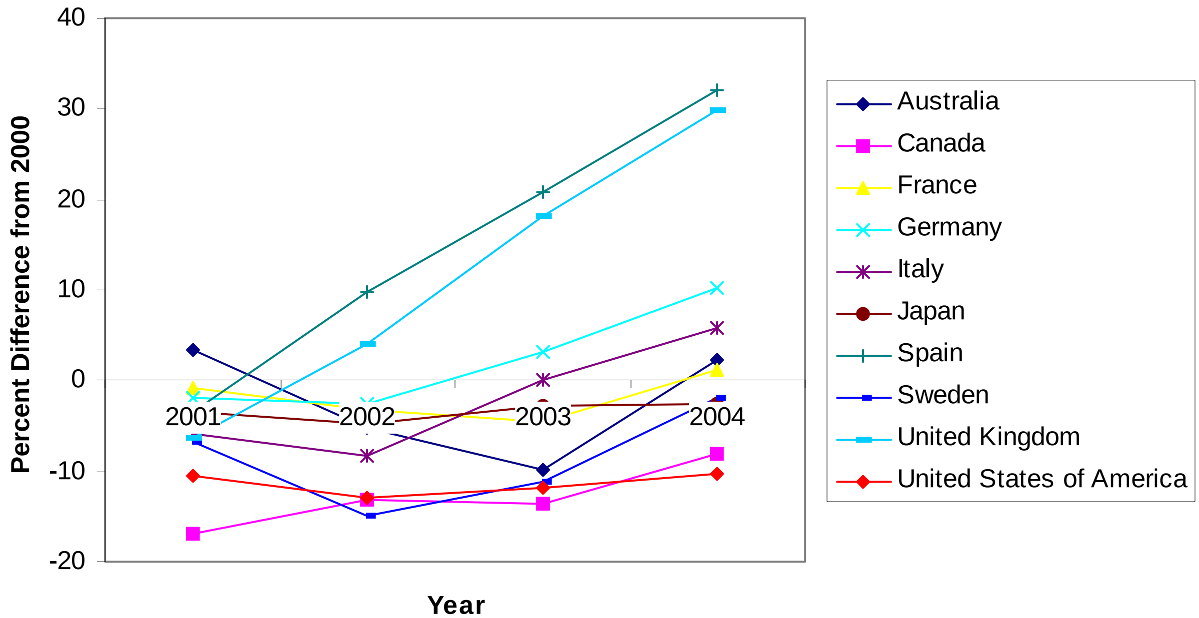

Figure 10. Trends in Total (Domestic plus International) Fuel Burn for Selected Countries

The domestic fuel burn percent changes shown in Figure 8 appear to show relatively constant fuel burns. However, the international percent changes in Figure 9 show increasing trends especially in the latter years (e.g., 2003 and 2004). Combining the domestic and international inventories in Figure 10 also shows similar increasing trends. Therefore, on an overall basis, it appears that the effects of 9/11 appear to be starting to wearing off, at least for these larger countries. It should also be noted that some of the decreases in fuel burn and emissions are not all due to 9/11, and could simply be due to changes in the economy that are unrelated to 9/11.

3.2 Aircraft Inventories

In SAGE, about 1000 unique aircraft-engine combinations are modeled each year. This large number of combinations is due to the distribution of engines used for each aircraft type and the modeling of each of the ETMS aircraft code variations (e.g., 732 and B732). Inventories of these unaggregated unique combinations on a per-flight total basis are provided in Appendix C. Potentially, a lot of the equivalent aircraft codes (e.g., ETMS as well as OAG codes) could be aggregated to conduct more meaningful aircraft-level analyses. As discussed in Section 2.1, piston-powered aircraft are excluded from these processed inventories due to the uncertainties associated with their EI values. Similar inventories on a modal basis are provided in Appendix D but aggregated by just aircraft type rather than aircraft-engine combinations. These processed inventories provide the potential for further processing to derive various summary statistics.

Expanding upon Table 4 in Section 3, global summary statistics for jets and turboprops are presented in Tables 13 and 14.

Table 13. Jet and Turboprop Global Totals

Aircraft Category	Year	Flights	Distance (nm)	Fuel Burn (Kg)	NOx (Kg)	CO (Kg)	HC (Kg)	CO_2 (Kg)	H_2O (Kg)	SOx (Kg)
Jet	2000	21016189	1.63E+10	1.77E+11	2.45E+09	5.11E+08	7.01E+07	5.59E+11	2.19E+11	1.42E+08
	2001	20781893	1.58E+10	1.66E+11	2.30E+09	4.41E+08	5.90E+07	5.25E+11	2.06E+11	1.33E+08
	2002	21477594	1.62E+10	1.67E+11	2.37E+09	4.56E+08	5.93E+07	5.28E+11	2.07E+11	1.34E+08
	2003	22495374	1.72E+10	1.73E+11	2.45E+09	4.64E+08	5.74E+07	5.46E+11	2.14E+11	1.39E+08
	2004	24085131	1.87E+10	1.85E+11	2.64E+09	4.89E+08	5.82E+07	5.84E+11	2.29E+11	1.48E+08
Turboprop	2000	8690098	1.78E+09	4.25E+09	5.69E+07	2.99E+07	5.52E+06	1.34E+10	5.25E+09	3.40E+06
	2001	6892035	1.41E+09	3.48E+09	4.86E+07	2.30E+07	3.95E+06	1.10E+10	4.31E+09	2.79E+06
	2002	6999806	1.45E+09	3.51E+09	4.85E+07	2.43E+07	4.63E+06	1.11E+10	4.34E+09	2.81E+06
	2003	6284663	1.35E+09	3.28E+09	4.70E+07	2.20E+07	4.25E+06	1.03E+10	4.06E+09	2.62E+06
	2004	6293462	1.35E+09	3.28E+09	4.68E+07	2.20E+07	4.35E+06	1.04E+10	4.06E+09	2.63E+06

Table 14. Jet and Turboprop Global Derived Metrics

Aircraft Category	Year	Fuel Burn/Flight (Kg/Flight)	Fuel Burn/Distance (Kg/nm)	EI NOx (g/Kg)	EI CO (g/Kg)	EI HC (g/Kg)
Jet	2000	8.43E+03	10.9	13.8	2.89	0.396
	2001	8.00E+03	10.5	13.8	2.65	0.355
	2002	7.79E+03	10.3	14.1	2.72	0.354
	2003	7.70E+03	10.0	14.1	2.68	0.332
	2004	7.68E+03	9.92	14.3	2.64	0.314
Turboprop	2000	4.89E+02	2.39	13.4	7.04	1.30
	2001	5.05E+02	2.47	14.0	6.60	1.13
	2002	5.01E+02	2.42	13.8	6.93	1.32
	2003	5.22E+02	2.44	14.3	6.70	1.30
	2004	5.22E+02	2.43	14.2	6.70	1.32

Similar to the regional and country statistics, fuel usage and emissions appear to generally decrease in 2001 and increase toward 2004 reflecting the effects of 9/11. In terms of fuel usage-efficiency, it appears that jets generally became more efficient (i.e., decreases in both fuel burn per flight and distance) while turboprops became either less efficient or stayed relatively similar from 2000 to 2004. These changes in fuel burn efficiency may be due to many different reasons including fleet mix, operations, etc.

By sorting the inventories in Appendix C, the aircraft types that contribute to at least 95% of global totals of number of flights, distance flown, fuel burn, and NOx emissions are presented in Tables 15 through 18.

Table 15. Aircraft Accounting for 95% of Global Total Flights

2000		2001		2002		2003		2004	
Aircraft	Flights	Aircraft	Flights	Aircraft	Flights	Aircraft	Flights	Aircraft	Flights
B733	2022386	B733	1970014	B733	1857061	A320	1894607	A320	2027919
MD80	1950605	B732	1696594	A320	1677076	B733	1808382	B733	1861023
B732	1762498	MD80	1695504	MD80	1638917	B732	1496957	E145	1388646
A320	1431459	A320	1545073	B732	1493923	MD80	1409717	B732	1344799
B190	1182301	B752	1131367	B752	1138743	E145	1169813	CRJ2	1234133
B752	1179444	DH8A	955725	E145	1078620	B752	1055830	CRJ1	1112130
DH8A	1060659	SF34	885431	CRJ1	988529	CRJ1	950948	B738	1085474
SF34	1025229	B190	813363	DH8A	892749	B738	918599	A319	1031951
E120	686461	E145	788373	B190	873145	A319	910664	B752	1016374
B735	674430	CRJ1	744652	SF34	781876	CRJ2	905074	B737	981330
CRJ1	655951	B735	637535	B738	738488	B190	808496	MD80	977474
B734	617496	B734	620664	A319	708233	B737	744435	B190	792186
B72Q	572679	DC9	603273	B734	677383	SF34	700892	SF34	713969
F100	570175	A319	598630	B735	666579	DH8A	683823	B735	692217
DC9	556404	BA46	566525	B737	554253	B735	630217	DH8A	667248
BA46	555932	E120	556999	B763	526928	B734	616336	B734	635195
E145	532609	F100	554629	CRJ2	491764	B763	506310	B763	516098
AT43	523629	B738	524016	BA46	478229	DC9	444623	AT72	485261
DC9Q	482051	AT43	466942	F100	448687	AT72	440115	A321	426905
B762	446365	B737	432213	E120	432629	BA46	427801	MD82	401242
B73Q	423347	B762	411350	AT72	408892	A321	337863	B744	375446
AT72	416456	AT72	407363	AT43	406420	B744	333207	BA46	374895
A319	407407	B763	396240	DC9	348744	F100	327921	CRJ7	350855
F50	399931	B72Q	345230	B744	309231	B772	320292	B772	346881
B763	376059	F50	323502	B762	304991	E120	308125	DH8C	331844
B737	356615	CRJ2	308597	F50	304668	AT43	305908	E135	316200
B738	311378	B73Q	284033	A321	304035	DH8C	290163	B712	300233
B744	305639	B744	282631	B772	302980	E135	269563	A306	295008
B722	293847	B772	274903	DH8C	286530	B762	262325	E120	289224
F28	293760	B722	264584	A306	258588	A306	257555	F100	282399
JS41	280472	D328	250892	JS41	224019	F50	255047	F50	255651
C208	273818	DC9Q	249502	D328	220372	B712	238126	B762	255352
B772	241223	B741	240688	C208	197638	C208	215496	C208	249398
DH8C	226546	A321	235871	B712	193035	CRJ7	197967	AT43	247088

D328	226425	A306	235574	E135	190027	D328	182686	DC9	220252
CARJ	218978	JS41	194731	DC93	185708	B73Q	176948	A332	206497
A321	217969	DH8C	194641	B72Q	185300	A332	173062	DH8D	190596
B741	201028	F28	191391	B741	184290	MD90	169538	MD90	175809
A310	195606	SW4A	186427	B73Q	180668	JS41	169380	DC93	167427
JS31	194436	MD90	173177	DHC6	161617	DC93	168020	MD83	161095
B721	192704	AT44	170689	MD90	153794	MD82	163370	DHC6	151719
SW4A	191866	A310	169537	A310	152844	DHC6	158971	T154	145681
DHC6	189638	DHC6	165834	SW4A	150084	DH8B	152090	DH8B	145562
DC10	180886	C208	146866	DH8B	142413	DH8D	145832	A343	143473
MD90	178960	B721	141988	AT44	140995	B741	144412	AT44	139421
A306	178589	B712	140582	A332	139892	B721	133175	JS41	139379
A330	175747	A330	130964	B722	137750	T154	126771	D328	135462
A30B	169156	DC10	126940	B721	135108	A343	124995	A310	126140
CRJ2	157076	JS31	126607	MD11	129162	A310	123987	SW4	119796
DH8B	150865	A30B	124082	SW4	126471	AT44	123205	MD11	117664
SW4	150336	E135	112825	A343	122907	MD11	119610	B741	116817
AT44	143115	MD11	112577	DH8D	121126	B72Q	111345	B721	116663
MD11	138469	E110	104377	DC10	115469	SW4A	111323	B722	115058
JS32	125821	SF20	99561	SF20	114122	SW4	110544	B73Q	106016
E110	124345	DH8B	95702	A30B	111939	J328	105624	SW4A	96902
SF20	121850	DC93	85826	T154	108431	A30B	99989	B72Q	96217
A340	113556	A340	79337	F28	100733	B722	96791	J328	91823
TU5	100275	F70	78452	J328	94676	DC10	90719	LJ35	88940
BE99	99462	MD82	74902	JS31	91679	F70	83763	DC10	84854
SH36	96074	MD83	70823	E110	86438	SF20	81964	BE99	84190
F70	83043	DH8D	67653	F70	83457	SH36	79525	BE20	84030
ATP	82206	TU34	66461	LJ35	82787	TU34	77371	B736	82945
B742	81419	T154	62166	BE20	81372	BE20	77149	F70	77582
C560	68735	ATP	61095	SH36	78434	LJ35	74929	SH36	75091
F27	65586	DC85	59768	BE99	76770	E110	72660	TU34	74901
LJ35	63565	SH36	57627	CRJ7	70222	JS32	71241	C560	74820
TU34	62725	JS32	56726	TU34	69702	BE99	68163	B773	73565
E135	61726	SW4	53513	C560	66789	JS31	64997	H25B	71662
BE20	60408	B736	53506	B736	60461	C560	64941	JS32	69767
AN12	53360	AN12	53498	H25B	59096	B736	64289	A333	69639
DC85	52550	J328	51412	BE40	56247	MD83	64277	A30B	69066
A748	52527	LJ35	51270	B742	50948	H25B	58034	C56X	68730
SW3	51818			DC95	50751	AN12	56495	BE40	66394
L101	50386			MD82	50662	BE40	55317	SF20	65763
B736	49701			F27	49620	B742	54229	RJ85	65164
				A333	48585	B773	53969	AT45	64959
				D228	48453	F28	53666	E110	64417
				AN12	48401	A333	53143	B742	62556
				ATP	47878	PC12	50637	AN12	59058
				PC12	47227	C56X	49195	B739	59056
				B773	46612	B462	48724	B753	56920
				JS32	45441	ATP	47423	DC95	55821
						DC95	47144	PC12	55721
						L410	43572	JS31	49903

								B462	49014
								DC9Q	48335

Table 16. Aircraft Accounting for 95% of Global Total Distance Flown

2000		2001		2002		2003		2004	
Aircraft	Distance (nm)	Aircraft	Distance (nm)	Aircraft	Distance (nm)	Aircraft	Distance (nm)	Aircraft	Distance (nm)
MD80	1.21E+09	A320	1.12E+09	A320	1.18E+09	A320	1.41E+09	A320	1.54E+09
B752	1.14E+09	B752	1.12E+09	B752	1.13E+09	B752	1.12E+09	B744	1.18E+09
B733	1.12E+09	B733	1.07E+09	B733	9.78E+08	B744	1.03E+09	B752	1.09E+09
A320	1.05E+09	MD80	1.03E+09	MD80	9.77E+08	B733	9.78E+08	B733	1.01E+09
B744	9.92E+08	B744	9.06E+08	B744	9.58E+08	B763	8.92E+08	B763	9.61E+08
B732	8.36E+08	B732	8.08E+08	B763	8.91E+08	MD80	8.31E+08	B738	9.03E+08
B763	7.87E+08	B763	7.60E+08	B732	7.17E+08	B738	7.37E+08	B772	8.11E+08
B762	5.45E+08	B741	6.32E+08	B772	6.57E+08	B732	7.24E+08	A319	7.23E+08
B741	4.79E+08	B772	5.71E+08	B738	5.95E+08	B772	7.15E+08	B737	7.05E+08
B772	4.69E+08	B762	5.33E+08	A319	4.82E+08	A319	6.61E+08	B732	6.48E+08
MD11	4.00E+08	A319	4.28E+08	B741	4.38E+08	B737	5.42E+08	E145	5.94E+08
B72Q	3.66E+08	B738	4.26E+08	B762	4.32E+08	E145	4.88E+08	CRJ2	5.32E+08
DC10	3.58E+08	B734	3.24E+08	CRJ1	4.12E+08	CRJ1	4.16E+08	MD80	4.86E+08
A340	3.49E+08	B737	3.22E+08	E145	4.12E+08	CRJ2	3.94E+08	CRJ1	4.77E+08
B734	3.44E+08	MD11	3.20E+08	B737	3.96E+08	A343	3.90E+08	A343	4.64E+08
B735	3.14E+08	E145	3.12E+08	A343	3.86E+08	B762	3.77E+08	A332	3.79E+08
A319	2.96E+08	CRJ1	3.04E+08	MD11	3.46E+08	B741	3.52E+08	B762	3.65E+08
B738	2.90E+08	B735	3.02E+08	B734	3.44E+08	B734	3.21E+08	B734	3.27E+08
A330	2.73E+08	DC9	2.61E+08	B735	2.98E+08	A332	3.19E+08	B735	3.26E+08
B737	2.64E+08	A340	2.51E+08	A332	2.52E+08	MD11	3.19E+08	MD82	3.18E+08
CRJ1	2.55E+08	DC10	2.29E+08	CRJ2	2.20E+08	B735	3.02E+08	A321	3.15E+08
B742	2.48E+08	F100	2.22E+08	A321	2.08E+08	A321	2.49E+08	MD11	3.02E+08
DC9	2.38E+08	B72Q	2.21E+08	DC10	2.04E+08	A306	2.03E+08	B741	2.69E+08
A310	2.34E+08	BA46	2.15E+08	A306	1.99E+08	DC9	1.88E+08	A306	2.33E+08
B190	2.30E+08	A310	2.03E+08	A310	1.87E+08	BA46	1.72E+08	CRJ7	1.80E+08
DC9Q	2.29E+08	A330	1.93E+08	F100	1.83E+08	A310	1.69E+08	A310	1.69E+08
F100	2.28E+08	B722	1.88E+08	BA46	1.80E+08	DC10	1.64E+08	B742	1.66E+08
B73Q	2.24E+08	A306	1.87E+08	B190	1.79E+08	B190	1.53E+08	B190	1.56E+08
BA46	2.12E+08	DH8A	1.78E+08	DH8A	1.70E+08	B742	1.50E+08	MD83	1.55E+08
E145	2.11E+08	SF34	1.76E+08	SF34	1.53E+08	SF34	1.36E+08	DC10	1.55E+08
SF34	2.07E+08	B190	1.67E+08	B742	1.51E+08	F100	1.36E+08	B712	1.50E+08
B722	2.05E+08	B73Q	1.52E+08	DC9	1.49E+08	DH8A	1.33E+08	BA46	1.45E+08
DH8A	1.99E+08	A321	1.43E+08	B72Q	1.16E+08	MD82	1.30E+08	A333	1.42E+08
A306	1.54E+08	A343	1.41E+08	T154	1.12E+08	T154	1.26E+08	T154	1.39E+08
E120	1.46E+08	CRJ2	1.37E+08	AT72	1.06E+08	B712	1.11E+08	SF34	1.39E+08
B721	1.19E+08	DC9Q	1.19E+08	B743	9.74E+07	AT72	1.08E+08	E135	1.27E+08
A321	1.11E+08	E120	1.11E+08	DC93	9.52E+07	E135	1.02E+08	DH8A	1.25E+08
A30B	1.09E+08	AT72	1.01E+08	B722	8.99E+07	A333	9.74E+07	AT72	1.19E+08
AT43	1.08E+08	AT43	9.51E+07	E120	8.82E+07	CRJ7	9.51E+07	F100	1.13E+08
F28	1.07E+08	B721	8.39E+07	B73Q	8.51E+07	B743	9.10E+07	DC9	9.45E+07
TU5	1.04E+08	A332	8.21E+07	AT43	8.31E+07	DC93	8.45E+07	B773	8.74E+07
B743	1.01E+08	MD90	7.91E+07	A333	8.09E+07	B721	7.92E+07	MD90	8.19E+07

CARJ	9.65E+07	A30B	7.45E+07	B721	7.77E+07	MD90	7.66E+07	DC93	7.92E+07
AT72	9.62E+07	F28	7.18E+07	B712	7.67E+07	DHC6	7.00E+07	B743	7.78E+07
F50	8.15E+07	D328	7.08E+07	A30B	7.13E+07	B73Q	6.92E+07	B722	7.33E+07
MD90	7.98E+07	B743	7.08E+07	E135	7.03E+07	B72Q	6.77E+07	B721	7.27E+07
L101	7.58E+07	F50	6.52E+07	MD90	6.94E+07	AT43	6.75E+07	B753	7.24E+07
CRJ2	7.12E+07	T154	6.40E+07	D328	6.62E+07	E120	6.59E+07	A346	7.17E+07
D328	6.53E+07	B742	6.38E+07	F50	5.77E+07	B722	6.51E+07	DHC6	7.12E+07
JS41	6.01E+07	B712	5.55E+07	DH8C	5.72E+07	A30B	6.42E+07	DH8C	6.68E+07
DC85	5.09E+07	MD83	5.55E+07	B773	4.89E+07	B773	5.91E+07	B764	6.44E+07
DH8C	4.68E+07	DC85	5.37E+07	TU34	4.66E+07	MD83	5.76E+07	B72Q	6.02E+07
DHC6	4.56E+07	MD82	4.95E+07	JS41	4.46E+07	DH8C	5.60E+07	E120	5.93E+07
B773	4.26E+07	B773	4.78E+07	LJ35	4.13E+07	TU34	5.42E+07	TU34	5.24E+07
TU34	4.19E+07	TU34	4.32E+07	MD82	3.91E+07	D328	5.38E+07	AT43	5.22E+07
F70	4.08E+07	E135	4.27E+07	F70	3.89E+07	B764	5.35E+07	DH8D	5.13E+07
SW4A	3.96E+07	TU5	4.02E+07	H25B	3.65E+07	F50	4.74E+07	F50	4.77E+07
C208	3.90E+07	F70	4.01E+07	F28	3.42E+07	B753	4.56E+07	B739	4.51E+07
SF20	3.69E+07	DC93	3.98E+07	SF20	3.30E+07	DH8D	4.03E+07	LJ35	4.41E+07
JS31	3.49E+07	DH8C	3.96E+07	SW4A	3.15E+07	LJ35	3.70E+07	H25B	4.38E+07
SW4	3.36E+07	JS41	3.94E+07	J328	3.12E+07	F70	3.70E+07	A30B	4.34E+07
IL62	3.27E+07	DHC6	3.94E+07	DC85	3.05E+07	H25B	3.53E+07	B736	3.90E+07
IL76	3.21E+07	SW4A	3.61E+07	DH8D	3.05E+07	JS41	3.50E+07	C208	3.66E+07
LJ35	3.07E+07	A333	3.59E+07	CRJ7	3.00E+07	C208	3.16E+07	D328	3.61E+07
C560	3.02E+07			C560	2.99E+07	B736	3.03E+07	C750	3.56E+07
DC87	2.98E+07			C208	2.97E+07	B739	3.02E+07	F70	3.55E+07
AT44	2.86E+07			SW4	2.88E+07	J328	2.99E+07	B73Q	3.46E+07
DC8Q	2.82E+07			CL60	2.76E+07	C560	2.94E+07	C560	3.40E+07
				DH8B	2.74E+07	DH8B	2.85E+07	C56X	3.39E+07
				IL76	2.70E+07	C750	2.82E+07	BE40	3.00E+07
				BE40	2.69E+07	CL60	2.53E+07	JS41	2.89E+07
				DHC6	2.63E+07	BE40	2.51E+07	RJ85	2.87E+07
				B736	2.60E+07	SW4A	2.47E+07	AT44	2.72E+07
				AT44	2.54E+07	A346	2.46E+07	CL60	2.70E+07
						C56X	2.39E+07	SW4	2.68E+07

Table 17. Aircraft Accounting for 95% of Global Total Fuel Burn

2000		2001		2002		2003		2004	
Aircraft	Fuel Burn (Kg)	Aircraft	Fuel Burn (Kg)	Aircraft	Fuel Burn (Kg)	Aircraft	Fuel Burn (Kg)	Aircraft	Fuel Burn (Kg)
MD80	1.03E+10	A320	7.98E+09	A320	8.46E+09	A320	1.00E+10	A320	1.09E+10
B752	9.80E+09	B752	9.46E+09	B752	9.55E+09	B752	9.38E+09	B744	2.87E+10
B733	7.71E+09	B733	7.24E+09	B733	6.65E+09	B744	2.48E+10	B752	9.20E+09
A320	7.48E+09	MD80	8.68E+09	MD80	8.25E+09	B733	6.60E+09	B733	6.86E+09
B744	2.38E+10	B744	2.18E+10	B744	2.31E+10	B763	9.67E+09	B763	1.04E+10
B732	6.12E+09	B732	5.89E+09	B763	9.66E+09	MD80	6.99E+09	B738	5.96E+09
B763	8.45E+09	B763	8.15E+09	B732	5.22E+09	B738	4.88E+09	B772	1.26E+10
B762	6.01E+09	B741	1.52E+10	B772	1.02E+10	B732	5.26E+09	A319	4.63E+09
B741	1.15E+10	B772	8.81E+09	B738	3.95E+09	B772	1.11E+10	B737	4.60E+09
B772	7.25E+09	B762	5.82E+09	A319	3.13E+09	A319	4.21E+09	B732	4.72E+09
MD11	7.16E+09	A319	2.76E+09	B741	1.05E+10	B737	3.52E+09	E145	2.05E+09

B72Q	3.93E+09	B738	2.83E+09	B762	4.72E+09	E145	1.69E+09	CRJ2	1.74E+09
DC10	6.06E+09	B734	2.36E+09	CRJ1	1.29E+09	CRJ1	1.29E+09	MD80	4.19E+09
A340	5.44E+09	B737	2.11E+09	E145	1.45E+09	CRJ2	1.28E+09	CRJ1	1.49E+09
B734	2.49E+09	MD11	5.71E+09	B737	2.59E+09	A343	6.12E+09	A343	7.27E+09
B735	2.25E+09	E145	1.10E+09	A343	6.03E+09	B762	4.12E+09	A332	5.47E+09
A319	1.92E+09	CRJ1	9.57E+08	MD11	6.22E+09	B741	8.45E+09	B762	3.99E+09
B738	1.92E+09	B735	2.13E+09	B734	2.51E+09	B734	2.33E+09	B734	2.38E+09
A330	3.47E+09	DC9	2.08E+09	B735	2.11E+09	A332	4.60E+09	B735	2.29E+09
B737	1.76E+09	A340	3.90E+09	A332	3.64E+09	MD11	5.74E+09	MD82	2.69E+09
CRJ1	8.36E+08	DC10	3.87E+09	CRJ2	7.09E+08	B735	2.11E+09	A321	2.52E+09
B742	6.54E+09	F100	1.38E+09	A321	1.69E+09	A321	2.00E+09	MD11	5.48E+09
DC9	1.91E+09	B72Q	2.33E+09	DC10	3.48E+09	A306	2.86E+09	B741	6.48E+09
A310	2.64E+09	BA46	1.49E+09	A306	2.81E+09	DC9	1.50E+09	A306	3.30E+09
B190	3.01E+08	A310	2.28E+09	A310	2.10E+09	BA46	1.17E+09	CRJ7	5.53E+08
DC9Q	1.87E+09	A330	2.47E+09	F100	1.13E+09	A310	1.87E+09	A310	1.88E+09
F100	1.44E+09	B722	1.87E+09	BA46	1.25E+09	DC10	2.79E+09	B742	4.42E+09
B73Q	1.74E+09	A306	2.63E+09	B190	2.26E+08	B190	2.00E+08	B190	2.00E+08
BA46	1.47E+09	DH8A	4.20E+08	DH8A	3.99E+08	B742	3.98E+09	MD83	1.28E+09
E145	7.47E+08	SF34	6.15E+08	SF34	5.38E+08	SF34	4.79E+08	DC10	2.65E+09
SF34	7.17E+08	B190	2.11E+08	B742	3.98E+09	F100	8.41E+08	B712	9.25E+08
B722	2.07E+09	B73Q	1.15E+09	DC9	1.19E+09	DH8A	3.08E+08	BA46	1.00E+09
DH8A	4.66E+08	A321	1.19E+09	B72Q	1.21E+09	MD82	1.09E+09	A333	1.78E+09
A306	2.17E+09	A343	2.20E+09	T154	1.27E+09	T154	1.45E+09	T154	1.60E+09
E120	2.88E+08	CRJ2	4.47E+08	AT72	3.15E+08	B712	6.94E+08	SF34	4.87E+08
B721	1.19E+09	DC9Q	9.53E+08	B743	2.32E+09	AT72	3.23E+08	E135	4.50E+08
A321	9.58E+08	E120	2.23E+08	DC93	7.41E+08	E135	3.64E+08	DH8A	2.90E+08
A30B	1.74E+09	AT72	3.03E+08	B722	9.03E+08	A333	1.24E+09	AT72	3.56E+08
AT43	2.47E+08	AT43	2.18E+08	E120	1.73E+08	CRJ7	2.96E+08	F100	6.91E+08
F28	6.22E+08	B721	8.40E+08	B73Q	6.52E+08	B743	2.17E+09	DC9	7.42E+08
TU5	1.18E+09	A332	1.17E+09	AT43	1.89E+08	DC93	6.56E+08	B773	1.59E+09
B743	2.40E+09	MD90	6.90E+08	A333	1.04E+09	B721	7.93E+08	MD90	7.12E+08
CARJ	4.62E+08	A30B	1.20E+09	B721	7.84E+08	MD90	6.69E+08	DC93	6.25E+08
AT72	2.93E+08	F28	4.11E+08	B712	4.90E+08	DHC6	6.72E+07	B743	1.84E+09
F50	2.40E+08	D328	1.88E+08	A30B	1.14E+09	B73Q	5.50E+08	B722	7.47E+08
MD90	7.10E+08	B743	1.70E+09	E135	2.52E+08	B72Q	7.06E+08	B721	7.25E+08
L101	1.19E+09	F50	1.92E+08	MD90	6.10E+08	AT43	1.50E+08	B753	6.49E+08
CRJ2	2.39E+08	T154	7.27E+08	D328	1.72E+08	E120	1.26E+08	A346	1.11E+09
D328	1.68E+08	B742	1.70E+09	F50	1.72E+08	B722	6.53E+08	DHC6	6.82E+07
JS41	1.15E+08	B712	3.59E+08	DH8C	1.16E+08	A30B	1.03E+09	DH8C	1.35E+08
DC85	5.40E+08	MD83	4.71E+08	B773	8.95E+08	B773	1.08E+09	B764	7.39E+08
		DC85	5.78E+08	TU34	2.89E+08	MD83	4.78E+08	B72Q	6.30E+08
						DH8C	1.15E+08	E120	1.14E+08
						TU34	3.32E+08	TU34	3.21E+08
						D328	1.39E+08		
						B764	6.15E+08		

Table 18. Aircraft Accounting for 95% of Global Total NOx Emissions

2000	2001	2002	2003	2004

Aircraft	NOx (g)	Aircraft	NOx (g)	Aircraft	NOx (g)	Aircraft	NOx (g)	Aircraft	NOx (g)
MD80	8.87E+10	A320	1.12E+11	A320	1.27E+11	A320	1.44E+11	A320	1.57E+11
B752	1.07E+11	B752	1.24E+11	B752	1.24E+11	B752	1.20E+11	B744	4.38E+11
B733	6.05E+10	B733	8.32E+10	B733	7.66E+10	B744	3.81E+11	B752	1.19E+11
A320	1.06E+11	MD80	8.93E+10	MD80	8.55E+10	B733	7.57E+10	B733	7.87E+10
B744	1.55E+09	B744	3.16E+11	B744	3.54E+11	B763	1.28E+11	B763	1.39E+11
B732	1.26E+11	B732	5.82E+10	B763	1.27E+11	MD80	7.25E+10	B738	8.70E+10
B763	4.83E+09	B763	1.06E+11	B732	5.20E+10	B738	7.15E+10	B772	2.43E+11
B762	1.57E+10	B741	2.56E+11	B772	1.93E+11	B732	5.24E+10	A319	6.05E+10
B741	2.80E+09	B772	1.64E+11	B738	5.79E+10	B772	2.12E+11	B737	6.58E+10
B772	2.62E+10	B762	8.22E+10	A319	4.23E+10	A319	5.53E+10	B732	4.71E+10
MD11	6.98E+09	A319	3.62E+10	B741	1.78E+11	B737	5.03E+10	E145	2.61E+10
B72Q	3.03E+10	B738	4.15E+10	B762	6.59E+10	E145	2.20E+10	CRJ2	1.42E+10
DC10	3.94E+10	B734	2.89E+10	CRJ1	1.06E+10	CRJ1	1.07E+10	MD80	4.46E+10
A340	1.28E+10	B737	3.00E+10	E145	1.81E+10	CRJ2	1.05E+10	CRJ1	1.22E+10
B734	2.02E+10	MD11	8.35E+10	B737	3.71E+10	A343	1.06E+11	A343	1.26E+11
B735	1.37E+10	E145	1.43E+10	A343	1.04E+11	B762	5.72E+10	A332	9.73E+10
A319	9.60E+09	CRJ1	7.90E+09	MD11	9.08E+10	B741	1.42E+11	B762	5.49E+10
B738	2.48E+09	B735	2.46E+10	B734	3.09E+10	B734	2.85E+10	B734	2.92E+10
A330	1.91E+10	DC9	2.20E+10	B735	2.45E+10	A332	7.74E+10	B735	2.65E+10
B737	8.65E+10	A340	6.62E+10	A332	5.91E+10	MD11	8.42E+10	MD82	2.74E+10
CRJ1	2.02E+10	DC10	5.92E+10	CRJ2	5.80E+09	B735	2.44E+10	A321	4.28E+10
B742	4.25E+09	F100	1.22E+10	A321	2.98E+10	A321	3.39E+10	MD11	8.06E+10
DC9	2.58E+10	B72Q	2.33E+10	DC10	5.58E+10	A306	4.50E+10	B741	1.10E+11
A310	3.68E+09	BA46	1.37E+10	A306	4.42E+10	DC9	1.60E+10	A306	5.33E+10
B190	1.12E+11	A310	3.21E+10	A310	2.95E+10	BA46	1.09E+10	CRJ7	4.78E+09
DC9Q	2.52E+10	A330	4.23E+10	F100	1.00E+10	A310	2.59E+10	A310	2.59E+10
F100	2.78E+10	B722	1.72E+10	BA46	1.18E+10	DC10	4.40E+10	B742	7.45E+10
B73Q	3.55E+11	A306	4.10E+10	B190	1.15E+09	B190	1.03E+09	B190	1.03E+09
BA46	1.94E+10	DH8A	4.40E+09	DH8A	4.16E+09	B742	6.73E+10	MD83	1.33E+10
E145	7.98E+09	SF34	1.37E+10	SF34	1.20E+10	SF34	1.07E+10	DC10	4.16E+10
SF34	1.25E+09	B190	1.08E+09	B742	6.65E+10	F100	7.43E+09	B712	1.25E+10
B722	2.23E+08	B73Q	1.33E+10	DC9	1.26E+10	DH8A	3.18E+09	BA46	9.21E+09
DH8A	1.38E+11	A321	2.14E+10	B72Q	1.22E+10	MD82	1.12E+10	A333	2.81E+10
A306	1.11E+09	A343	3.77E+10	T154	2.44E+09	T154	2.87E+09	T154	2.81E+09
E120	2.41E+09	CRJ2	3.66E+09	AT72	4.55E+09	B712	9.40E+09	SF34	1.08E+10
B721	4.38E+09	DC9Q	9.78E+09	B743	3.81E+10	AT72	4.69E+09	E135	6.28E+09
A321	1.73E+10	E120	2.04E+09	DC93	7.59E+09	E135	5.08E+09	DH8A	3.01E+09
A30B	1.94E+11	AT72	4.42E+09	B722	8.43E+09	A333	1.96E+10	AT72	5.17E+09
AT43	3.83E+10	AT43	2.20E+09	E120	1.73E+09	CRJ7	2.57E+09	F100	6.08E+09
F28	6.91E+08	B721	8.07E+09	B73Q	7.73E+09	B743	3.45E+10	DC9	7.92E+09
TU5	1.16E+10	A332	2.08E+10	AT43	1.91E+09	DC93	6.71E+09	B773	3.43E+10
B743	1.85E+08	MD90	1.26E+10	A333	1.65E+10	B721	7.67E+09	MD90	1.30E+10
CARJ	3.28E+08	A30B	2.07E+10	B721	7.67E+09	MD90	1.23E+10	DC93	6.42E+09
AT72	9.65E+10	F28	5.21E+09	B712	6.75E+09	DHC6	4.59E+08	B743	3.02E+10
F50	1.31E+10	D328	2.68E+09	A30B	1.97E+10	B73Q	6.66E+09	B722	7.09E+09
MD90	3.62E+10	B743	2.89E+10	E135	3.49E+09	B72Q	7.21E+09	B721	6.97E+09
L101	5.52E+10	F50	2.95E+09	MD90	1.12E+10	AT43	1.53E+09	B753	7.99E+09
CRJ2	2.97E+10	T154	2.11E+09	D328	2.41E+09	E120	1.25E+09	A346	1.47E+10
D328	1.99E+09	B742	2.95E+10			B722	6.12E+09		

JS41	8.84E+08					A30B	1.78E+10
DC85	3.24E+08					B773	2.37E+10
DH8C	6.73E+08						
DHC6	1.04E+11						
B773	3.19E+08						
TU34	1.65E+08						
F70	1.94E+09						
SW4A	9.24E+10						
C208	3.67E+09						
SF20	1.49E+08						
JS31	2.13E+08						
SW4	2.10E+09						
IL62	7.01E+08						
IL76	1.15E+11						
LJ35	3.56E+08						
C560	3.17E+08						
DC87	5.01E+08						
AT44	2.31E+09						
DC8Q	1.23E+09						
DH8B	2.29E+07						
B757	3.30E+09						
E135	2.92E+09						
B736	1.00E+08						
B727	1.93E+08						
E110	1.81E+10						
B712	2.14E+09						
BE99	1.90E+09						

The ranked lists in Tables 15 through 18 are intuitive in that, as expected, the more popular aircraft such as the MD80, B752, B733, and A320 are generally at the top of each list. These lists also exemplify the understanding that the most used (e.g., most flown) aircraft are not necessarily the most fuel-consuming or most emissions-generating aircraft. This could be due to various reasons not the least of which are technological (e.g., aircraft performance) and operational (e.g., trip distances, frequency of use, etc.).

3.3 Gridded Inventories

The 4D gridded inventories described in Section 2.3 are typically processed to aggregate fuel burn and emissions into 1^o latitude by 1^o longitude by 1 km world grids. Since the raw inventory contains the actual time a flight entered into each of these grids, the inventory can be processed into any time segments (e.g., minute, hour, day, month, etc.). For faster querying of the data, monthly aggregated totals have been pre-generated. Due to the size of this processed data and the lack of usefulness, the data for each individual gridded are not included in this report. However, summary statistics are provided to show the geographical distributions of fuel burn and emissions. This was done using the processed data for 2000 as an example. Overall global plots of fuel burn with all altitudes aggregated are shown in Figures 11 through 14.

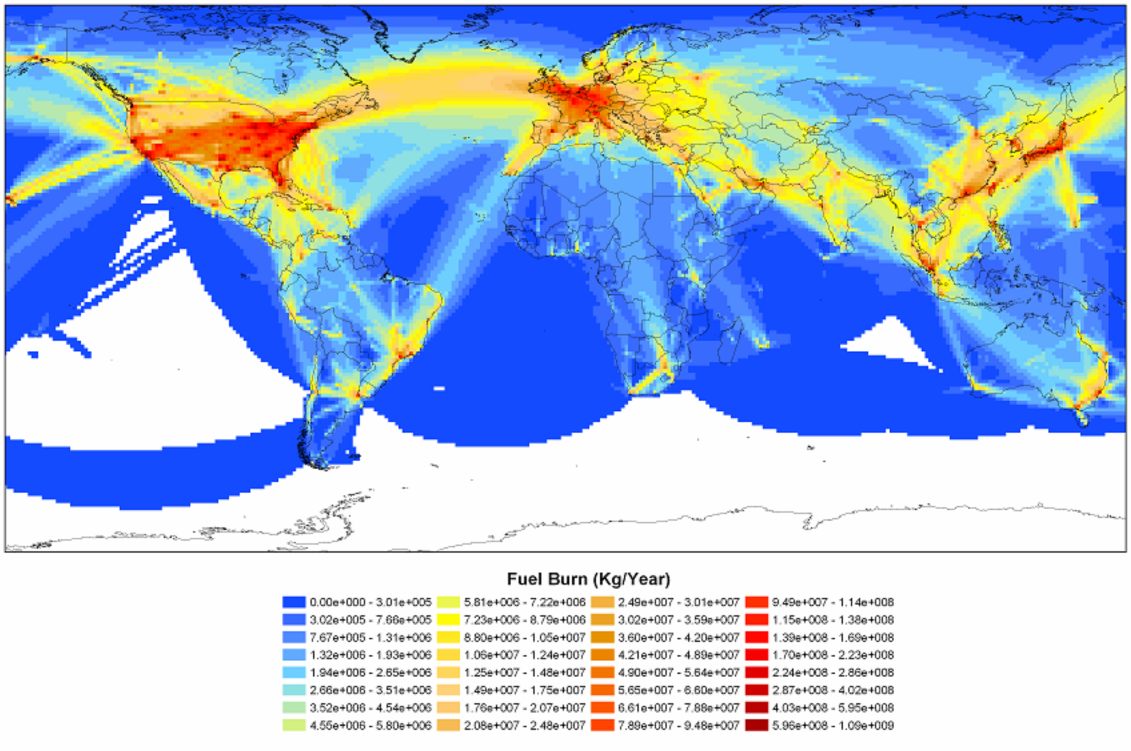

Figure 11. Gridded Plot of Global Fuel Burn for 2000 with all Altitudes Aggregated

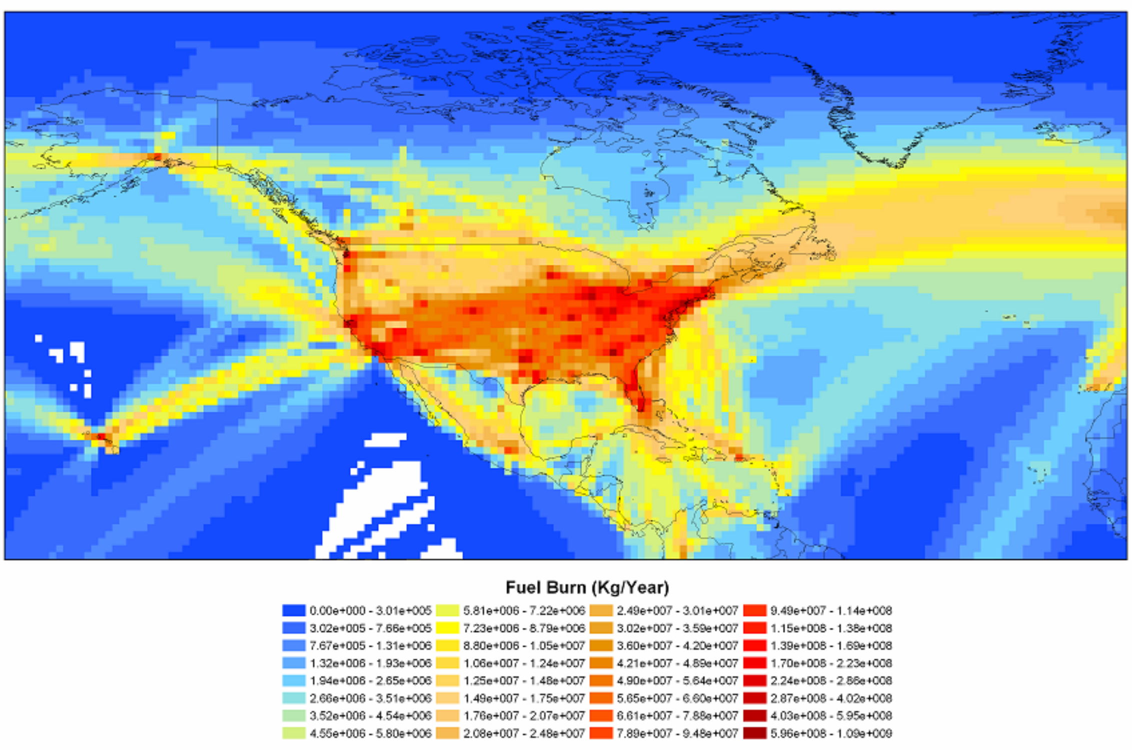

Figure 12. Gridded Plot of North American Fuel Burn for 2000 with all Altitudes Aggregated

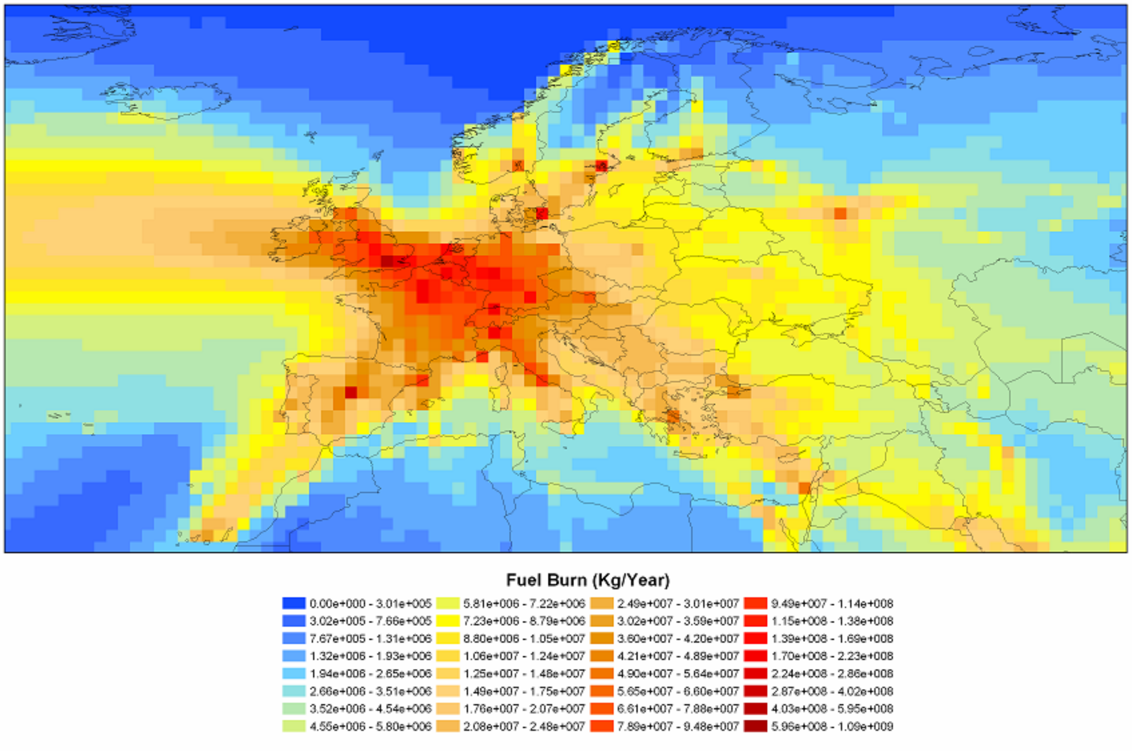

Figure 13. Gridded Plot European Fuel Burn for 2000 with all Altitudes Aggregated

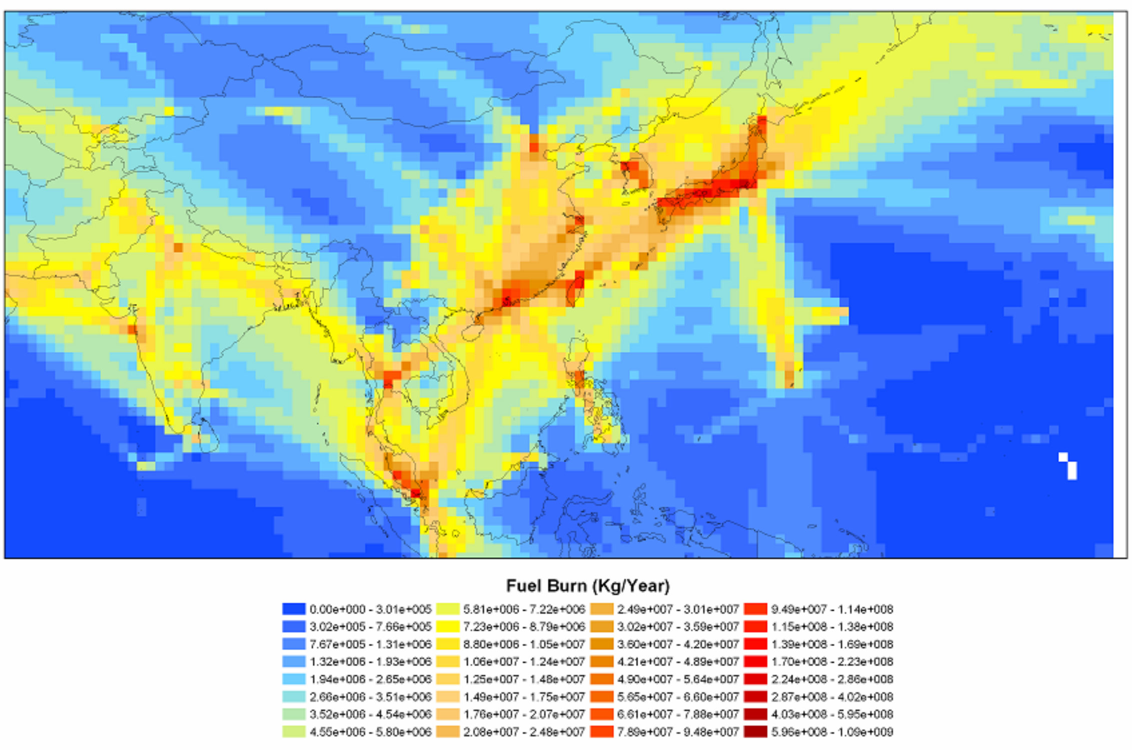

Figure 14. Gridded Plot of Asian Fuel Burn for 2000 with all Altitudes Aggregated

These gridded plots provide a visual confirmation of the fuel burn hot spots which are predominantly the US, Western Europe, and Eastern Asia. Emissions hot spots are also similarly located as they generally follow fuel burn. Figure 15 shows a distribution of total fuel burn and emissions by 1 km altitude bins for year 2000.

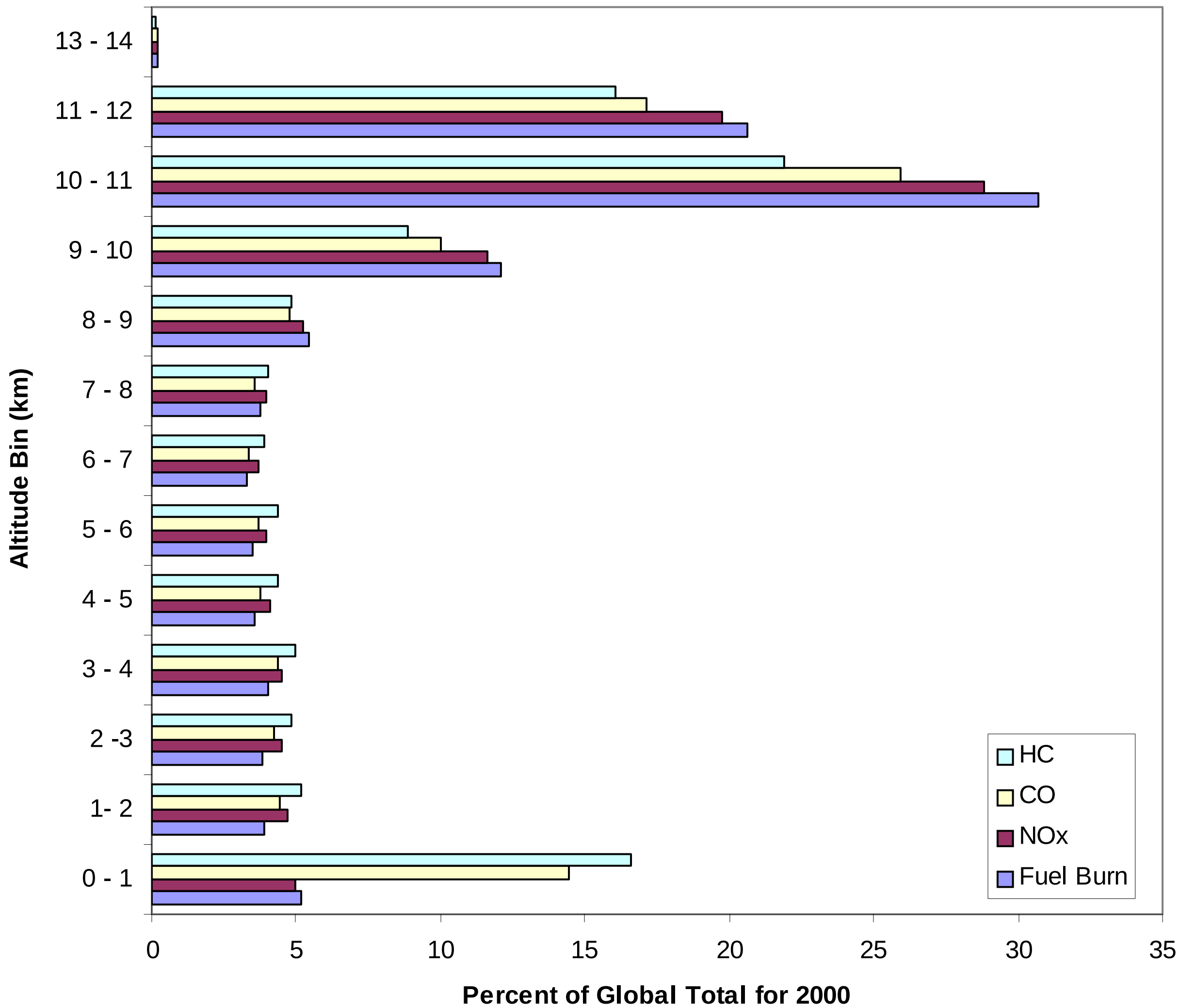

Figure 15. Altitude Distribution of Fuel Burn and Emissions for Year 2000

The altitude bins with the highest fuel burn and emissions are between 9 and 12 km (or approximately 29,500 ft and 39,400 ft). This corresponds to the frequent use of these altitudes for en route travel. The relatively high levels of HC and CO in the 0 to 1 km band is due to the higher emissions characteristics for those pollutants at lower power settings (e.g., during taxiing and idle conditions). Similar distributions by longitude and latitude are shown in Figures 16 and 17.

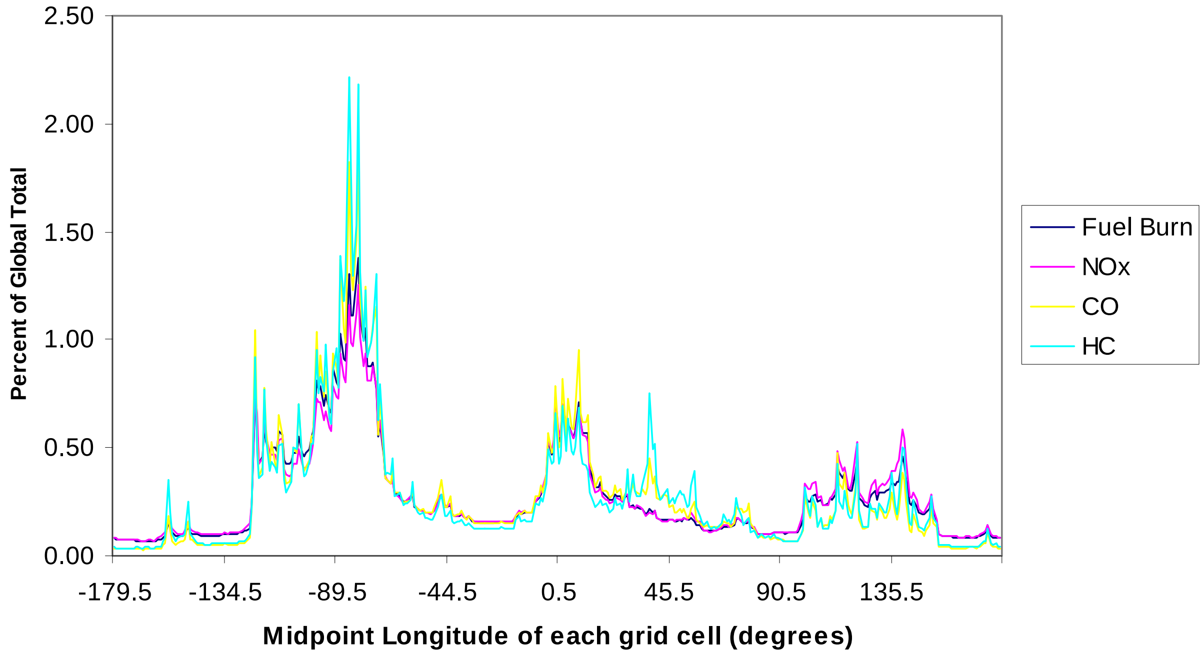

Figure 16. Distribution of Fuel Burn and Emissions by Longitude

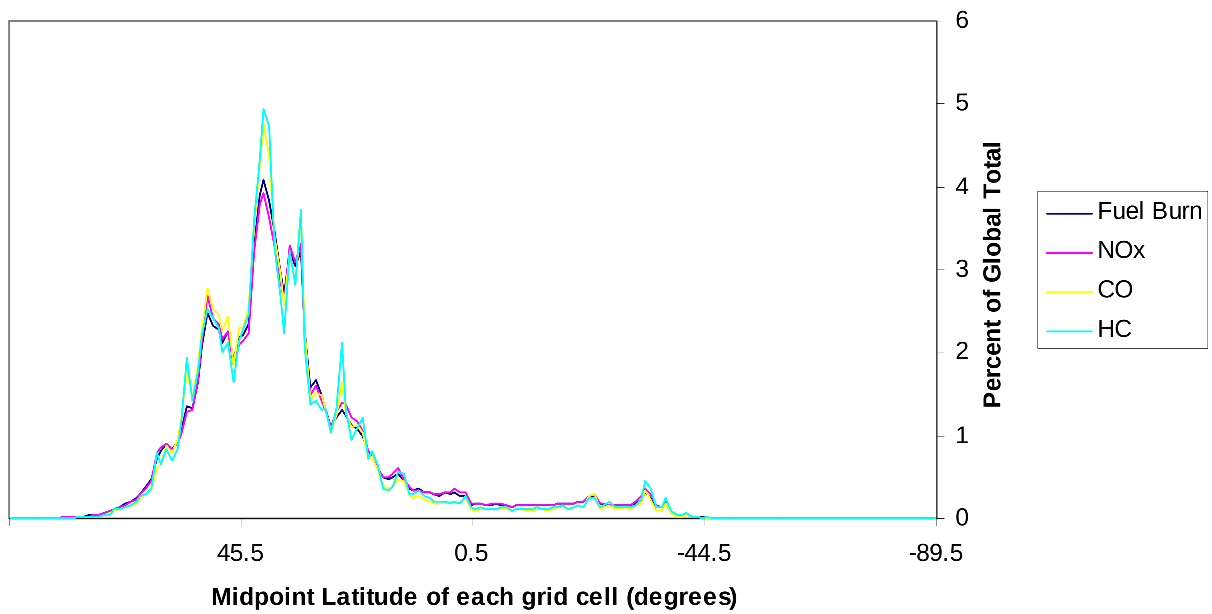

Figure 17. Distribution of Fuel Burn and Emissions by Latitude

As with the altitude distributions, NOx is shown to follow fuel burn more closely than CO or HC in these longitudinal and latitudinal distributions. The three peak sections in Figure 16 roughly correspond to North America, Western Europe, and Eastern Asia. In contrast, the one peak section in Figure 17 roughly corresponds to the Northern hemisphere where all of these three regions are located. In combining the longitudinal and latitudinal distributions, the globe was divided into four major quadrants (e.g., North East, North West, etc.) as shown in Figure 18.

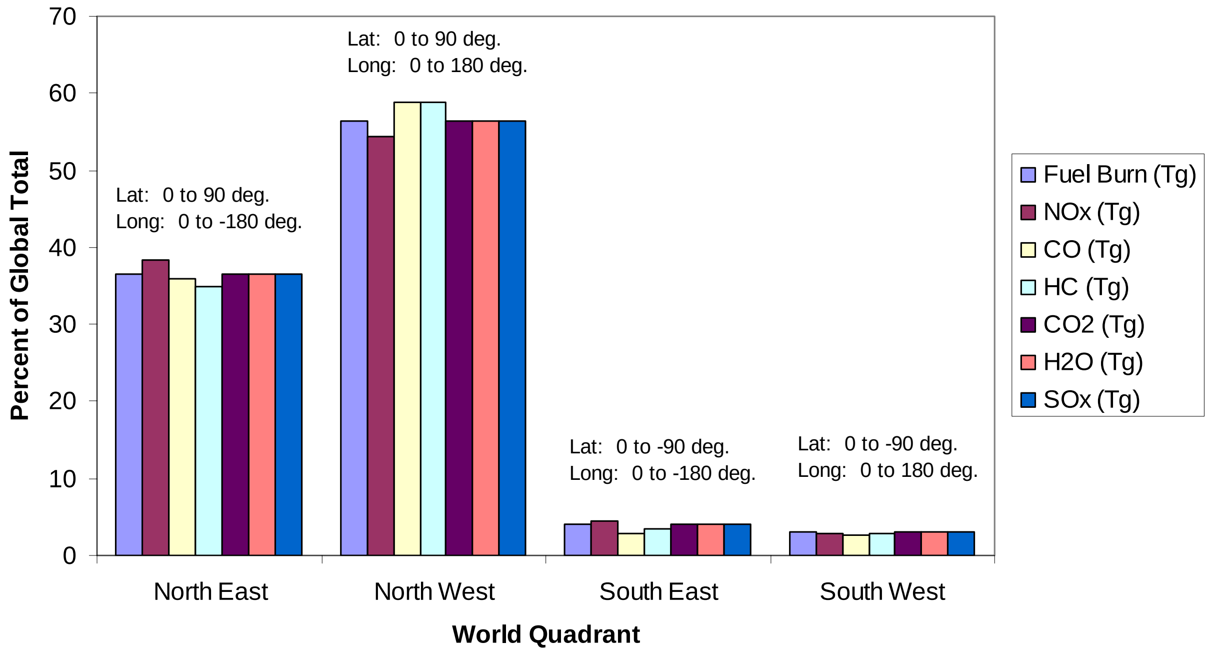

Figure 18. Relative Loadings of Fuel Burn and Emissions by World Quadrant

The much higher fuel burn and emissions levels experienced by the Northern quadrants are, again, mainly due to the flights over North America, Western Europe, and Eastern Asia.

4 Comparisons to Past Inventories

As SAGE follows upon various previous studies that have been conducted in the past to model global emissions from aircraft, comparisons to these past studies provide reasonability checks as well as wider views of historical trends that could help to better extrapolate to future years. Figures 19 through 23 show comparisons of SAGE global fuel burn and emissions with those from the following past studies [IPCC 1999]:

- NASA/Boeing inventories for 1976, 1984, 1992 and 1999 [Baughcum[a,b] 1996 and Sutkus 2001]
- ANCAT/EC2 inventories for 1991/92 [Gardner 1998]
- DLR inventories for 1992 [Schmitt 1997]
- AERO-MS inventories for 1992 [Pulles 2002]

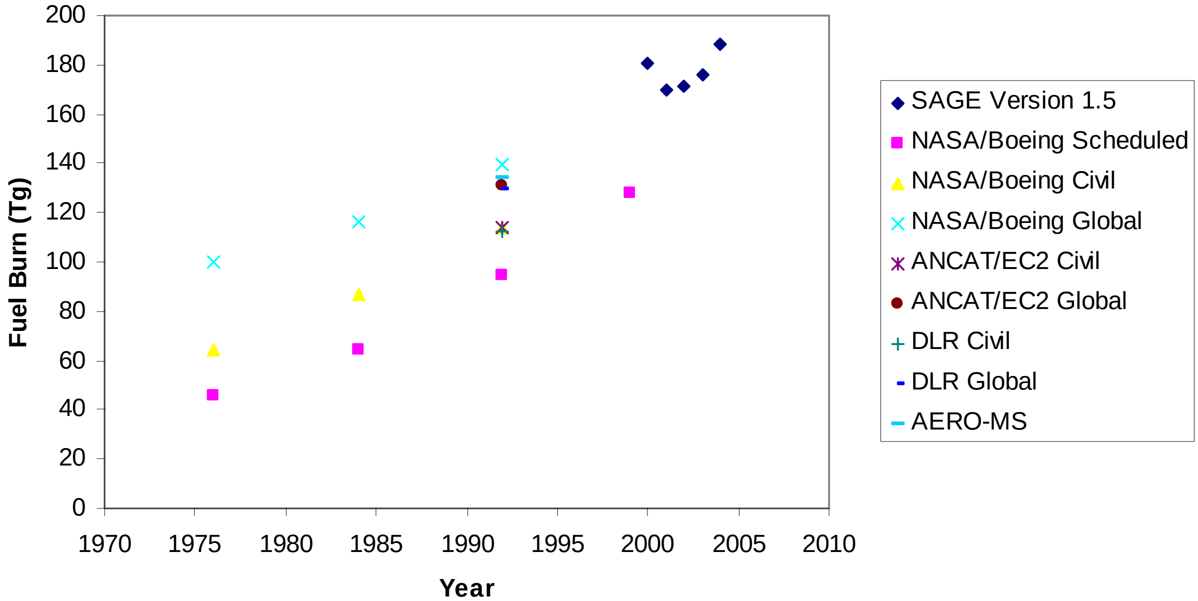

Figure 19. Comparison of Fuel Burn from Past Studies

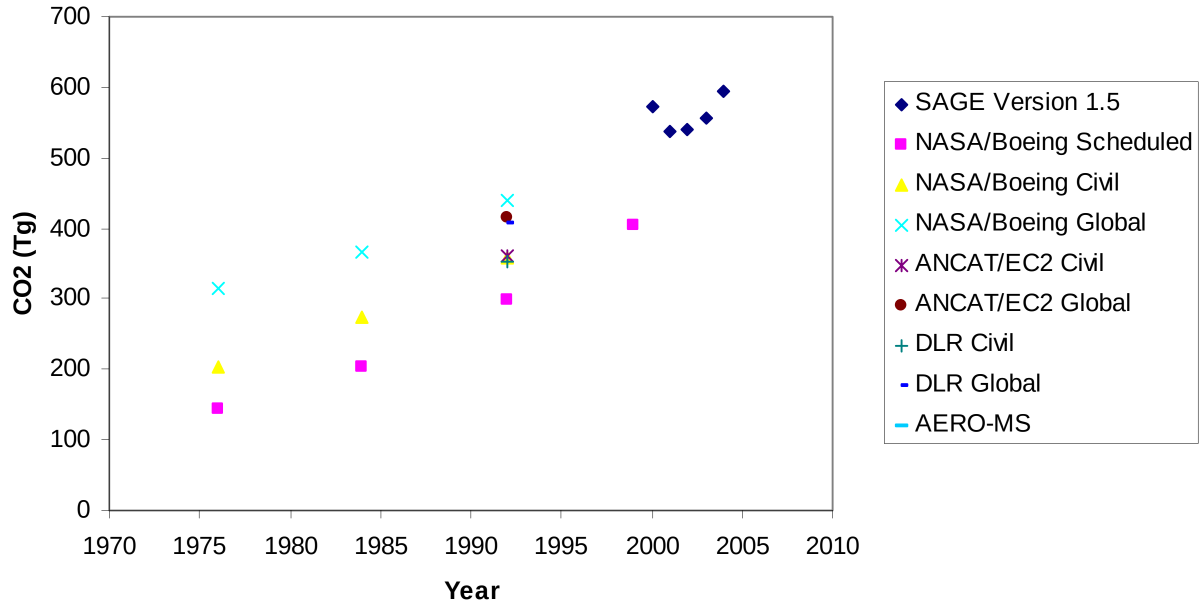

Figure 20. Comparison of CO_2 Emissions from Past Studies

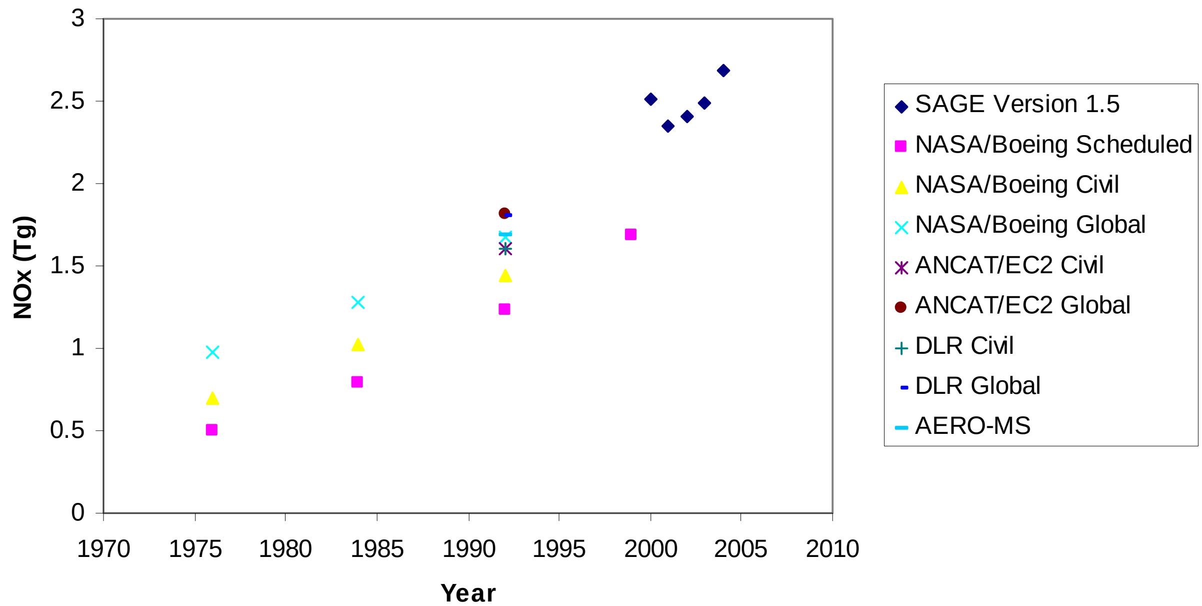

Figure 21. Comparison of NOx Emissions from Past Studies

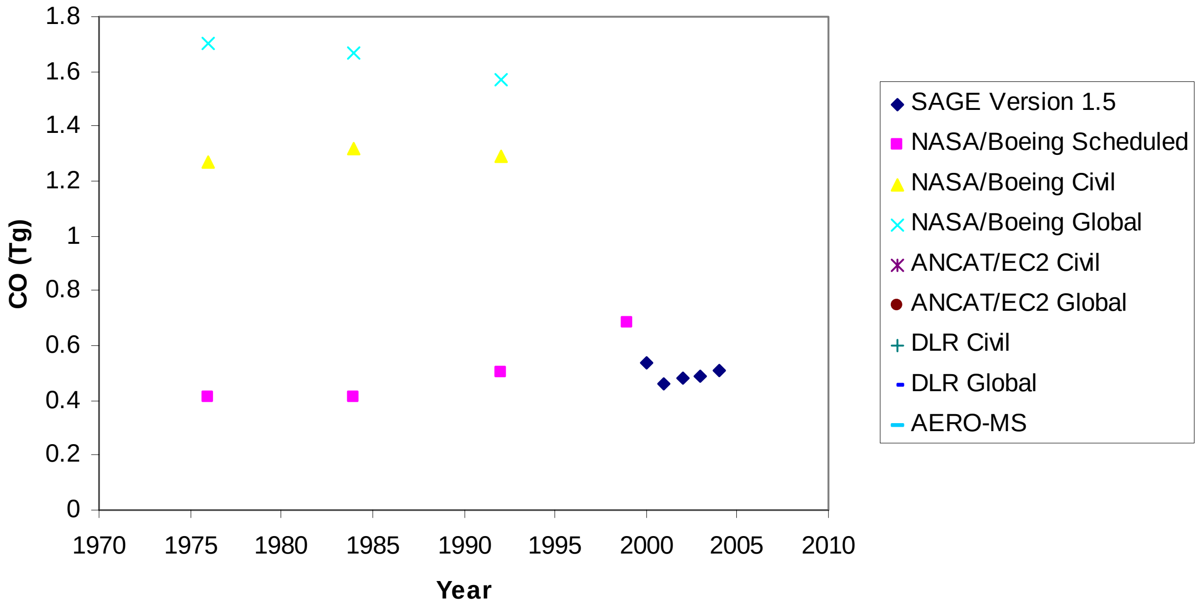

Figure 22. Comparison of CO Emissions from Past Studies

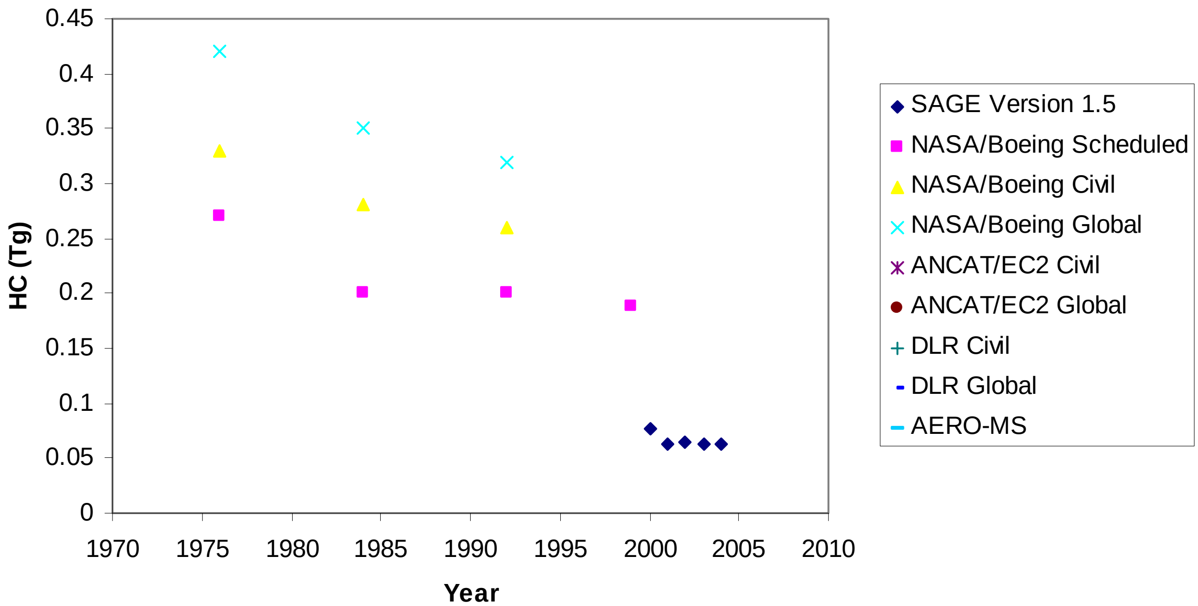

Figure 23. Comparison of HC Emissions from Past Studies

The plots in figures 19 though 21 (fuel burn, CO_2, and NOx) generally appear to show noticeable disagreement with the trends established from the past studies. Of all the past studies' data shown, the most appropriate comparison would be against the NASA/Boeing Scheduled inventories since SAGE Version 1.5 currently only accounts for commercial traffic. The past Civil and Global inventories include general aviation and military flights, respectively. Notwithstanding some natural growth in the aviation industry, the approximately 30% difference between the 1999 NASA/Boeing Scheduled inventory totals and the 2000 SAGE totals may in part be explained through differences in trajectory modeling (e.g., Great Circle used by NASA/Boeing versus track distributions used in SAGE) and the inclusion of the effects of unscheduled flights in SAGE (unaccounted in the NASA/Boeing studies). When general aviation and military flights are included in a future version of SAGE, a more appropriate comparison of global totals can be conducted. The CO and HC comparisons in Figures 22 and 23 indicate that SAGE are noticeably different than those suggested by the trends from the past studies. Notwithstanding the differences in distance modeling and unscheduled flights coverage, these types of disagreements with CO and HC are not unexpected since the two pollutants have a greater degree of variability with fuel flow than other pollutants like NOx. Unlike NOx, small changes in fuel flow could result in much larger changes in CO and HC due to the nature of the modeled relationship between fuel flow and EI values [FAA[a] 2005]. To investigate all of these differences further, the overall emissions indices for each of the pollutants were compared as shown in figures 24 through 26.

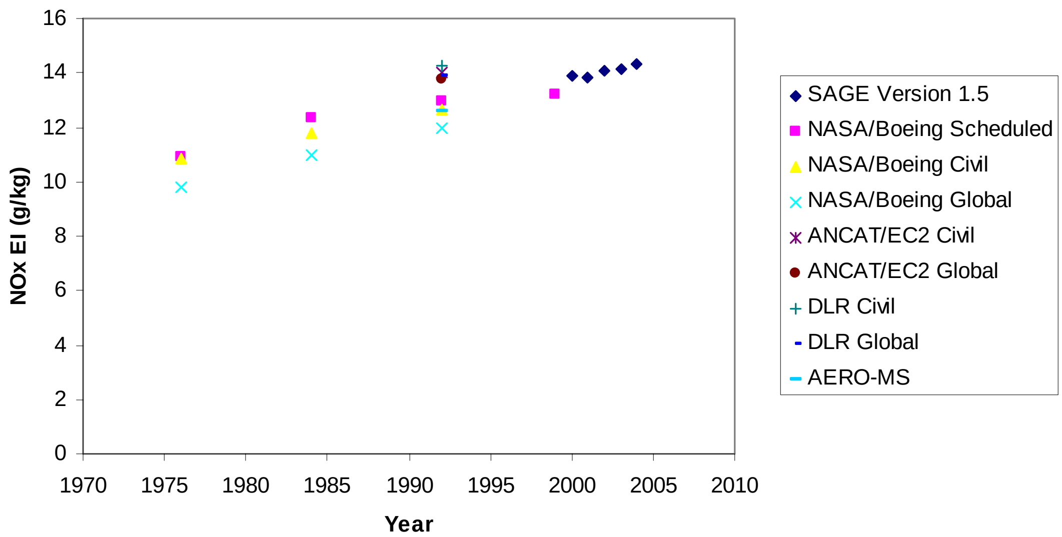

Figure 24. Comparison of SAGE Global Average NOx EI Values with Past Studies

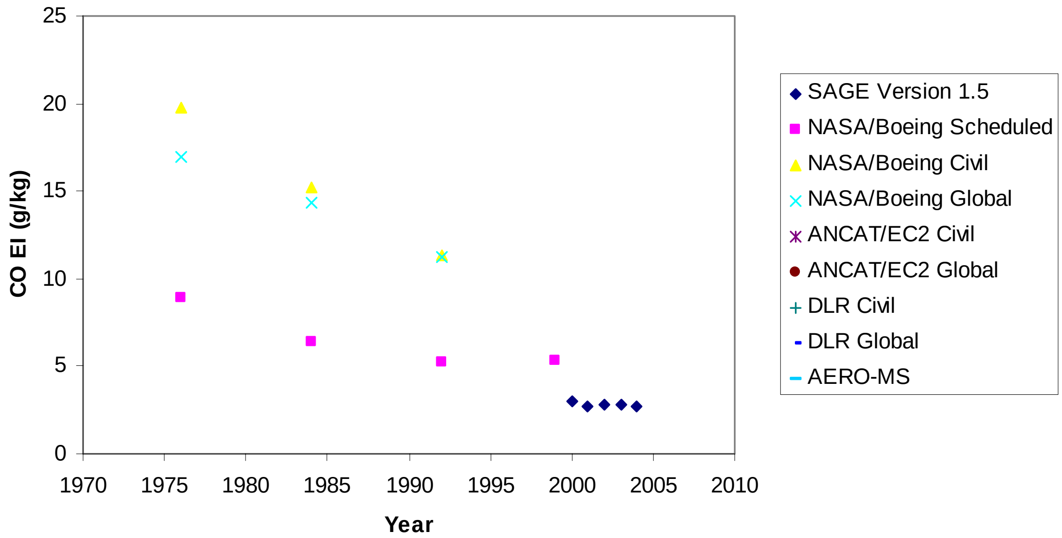

Figure 25. Comparison of SAGE Global Average CO EI Values with Past Studies

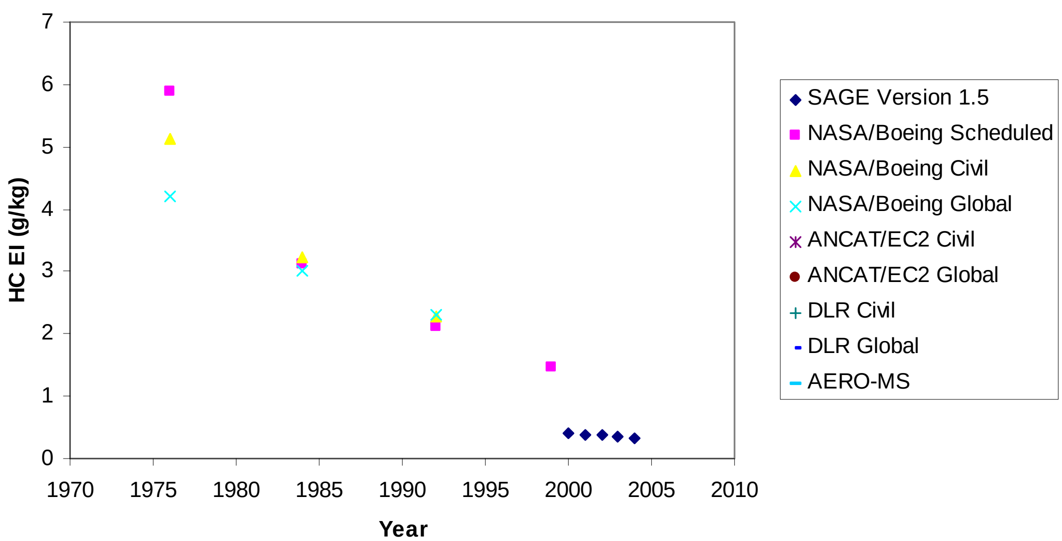

Figure 26. Comparison of SAGE Global Average HC EI Values with Past Studies

The NOx EI comparisons in Figure 24 appear to show relatively good agreement between the past studies' trends and those from SAGE. The difference between the 1999 NASA/Boeing Scheduled EI value and the 2000 SAGE value is about 5%. In contrast, the differences for CO and HC EI values are much greater as shown in figures 25 and 26. Also, the SAGE CO and HC EI values appear to be much less agreeable with the past studies' trends than for the NOx trends. These results indicate the differences in NOx totals (Figure 21) are less likely due to differences in EI modeling than the aforementioned differences in flight coverage, distance modeling, etc. However, the large differences in CO and HC EI values (figures 25 and 26) support the earlier assertion that the sensitivity of CO and HC EI values to fuel flow could have played a major role in the differences between CO and HC totals shown in figures 22 and

23. An aircraft-level comparison of a dozen selected aircraft types were conducted as shown in Figure 20.

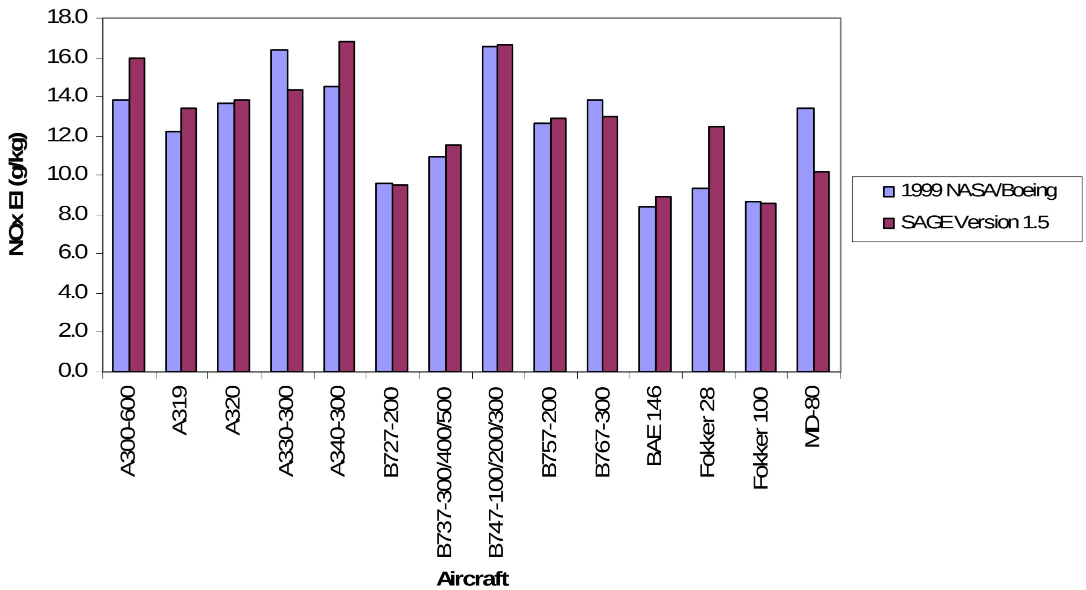

Figure 27. Comparison of Cruise (> 1 km Altitude above airport field elevation) NOx EI Values by Selected Aircraft Types from SAGE 2000 and NASA/Boeing 1999 Inventories

The aircraft shown in Figure 27 were arbitrarily selected, but they tend to be the most widely flown in the current world fleet. These NOx EI comparisons show reasonable agreement between the two datasets. Although a couple of aircraft types show noticeable differences such as the Fokker 28 (about 33%) and MD-80 (about 24%), most are within 15% difference. The differences in the EIs can be attributed to several factors including differences in the aircraft performance models (i.e., EI is dependent on fuel flow), differences in aircraft and engine mappings, operational changes of the world fleet from 1999 to 2000, and differences in engine assignments. The overall average EI values for the selected aircraft types are 13.2 g/kg for NASA/Boeing and 13.3 g/kg for SAGE Version 1.5. Similar to the comparisons in Figure 24, these values indicate that for the global fleet, the performance module in SAGE appears to produce comparable results to those from the past studies.

5 Conclusions

SAGE was developed by FAA in large part because there was no up-to-date non-proprietary model that could be used to estimate aircraft emissions on a global level. As such, FAA developed SAGE (now at Version 1.5) from the best publicly available data and methods in order to provide the international aviation community with a high-fidelity tool that can be used to analyze various policy, technology, and operational scenarios. So far, SAGE has been used to develop inventories for 2000-2004. The current commitment from FAA is to continue development and validation of SAGE to produce inventories of fuel burn and emissions on a yearly basis.

The flight-level, chord-level, and 4D gridded raw inventories provide high-resolution coverage of fuel burn and emissions as well as various flight parameters (e.g., aircraft performance data, flight schedule data, etc.). These inventories provide the potential for the development of numerous processed inventories to analyze various aspects of global aviation’s fuel burn and emissions including temporal trend analyses, event investigations (e.g., 9/11), and comparison assessments. The typical processed inventories presented in Sections 3.1 through 3.3 exemplify the uses of the data including the derivation of calculated metrics (e.g., fuel burn per distance, NOx EI values, etc.) that can be used to assess the effects of policy, technology, and operational changes to global aviation. Since the raw inventories were too large to include in this report, several processed inventories are included in the appendices in order to simulate the details and comprehensiveness of the raw inventories. In providing this data, a balance was chosen to provide as much useful data as possible but within reasonable limits to keep the data size manageable.

In general, most of the processed inventories presented in Sections 3.1 through 3.3 are intuitive. That is, trends, relative comparisons, et cetera appear to agree with the current understanding and state of the aviation industry. The comparison against previous studies showed noticeable differences in the overall, global fuel burn and emissions estimates. The SAGE fuel burn and NOx results appeared to be approximately 30% greater than that expected from the trends exhibited from the previous studies. Since the comparison of NOx EI values on both global and aircraft levels showed good agreement, the performance model in SAGE appears to be of comparable quality to those used in past studies. Therefore, most of the differences in the overall fuel burn and NOx estimates are likely to be due to differences in trajectory modeling, unscheduled flight coverage, etc.

The development of SAGE Version 1.5 and the inventories for 2000 through 2004 are based on the goal to provide FAA, and indirectly the international aviation community, with a standard and open model that can be used to generate high-fidelity global inventories of fuel burn and emissions in helping to answer various policy, technology, and operational questions. FAA is committed to supporting the continued development and validation of SAGE in producing yearly inventories of fuel burn and emissions. Therefore, the data and methods within SAGE and the inventories generated thereof will stay relevant year after year.

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APPENDICIES